



Prepared for:

USEPA Region 8

**The Lowry Landfill Superfund Site  
Work Settling Defendants**

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In conjunction with:

**Colorado Department of Public Health and the  
Environment**

**Tri-County Health Department**

**Waste Management**

**City and County of Denver**

# **Draft Updated Conceptual Site Model**

**Lowry Landfill NPL Site**

**EPA Site ID No. COD980499248**

**Arapahoe County, Colorado**

**April 30, 2021**

# Lowry Landfill Superfund Site Conceptual Site Model

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## ACRONYMS AND ABBREVIATIONS

3DVA	3-dimensional data visualization
amsl	Above mean sea level
AOC	Administrative Order on Consent
ATSDR	Agency for Toxic Substances and Disease Registry
BDCM	Bromodichloromethane
bgs	Below ground surface
BTS	Biological treatment system
CBSG	Colorado Basic Standard for Groundwater
CDM	Camp Dresser & McKee, Inc.
CDPHE	Colorado Department of Health and Environment
CGS	Colorado Geological survey
COC	Contaminants of concern
CSE	Containment System Evaluation
CSM	Conceptual site model
CWM	Chemical Waste Management, Inc.
DADS	Denver Arapahoe Disposal Site
DBF	DADS Blower/Flare
DCA	Dichloroethane
DDD	Dichlorodiphenyldichloroethane
DDT	Dichlorodiphenyltrichloroethane
DNAPL	Dense non-aqueous phase liquid
ECB	European Chemicals Bureau
ECOC	Ecological contaminants of concern
EE/CA	Engineering Evaluation/Cost Analysis
EMSI	Engineering Management Support, Inc.
EPA	U.S. Environmental Protection Agency
ESD	Explanation of Significant Differences
FS3	Flare Station 3
FS	Feasibility Study
FTPA	Former Tire Pile Area
GAC	Granular activated carbon
GTEP	Gas-to-energy plant
GWMP	Groundwater Monitoring Plan
HI	Hazard index
HLA	Harding Lawson Associates, Inc.
HSI	Hydro-Search, Inc.
HQ	Hazard quotient
IC	Institutional control
ITRC	Interstate Technology Regulatory Council
Kh	Hydraulic conductivity
LFG	Landfill gas
LLSS	Lowry Landfill Superfund Site
LNAPL	Light non-aqueous phase liquid
LOAEL	Lowest observable adverse effect level

## ACRONYMS AND ABBREVIATIONS (cont'd)

Metro	Metro Wastewater Reclamation District
mg/kg	Milligram(s) per kilogram
µg/dl	Micrograms per deciliter
µg/L	Microgram(s) per liter
mg/L	Milligram(s) per liter
MW	Monitoring Well
NAPL	Nonaqueous-phase liquid
NBBW	North Boundary Barrier Wall
NERA	North End Response Actions
NPL	National Priorities List
NTES	North Toe Extraction System
NYSPI	New York State Pollution Prevention Institute
O&M	Operations and maintenance
OU	Operable unit
PAH	Polyaromatic hydrocarbons
PCB	Polychlorinated biphenyls
PCE	Tetrachloroethene
POA	Point of action
POC	Points of compliance
POTW	Publicly owned treatment works
PQL	Practical quantitation Limit
PRP	Potentially Responsible Parties
PWT	Pacific Western Technologies
RAO	Remedial action objectives
RD/RA	Remedial Design/Remedial Action
RI	Remedial investigations
RME	Reasonable maximum exposure
ROD	Record of Decision
RSL	EPA regional screening levels
scfm	Standard cubic feet per minute
SSR	Site Status Reports
SVOC	Semi volatile organic compound
SWRA	Surface water removal action
TCA	Trichloroethane
TCDD	Tetrachlorodibenzodioxin
TCHD	Tri-County Health Department
TCE	Trichloroethene
TCLP	Toxicity characteristic leaching procedure
UAO	Unilateral Administrative Order
UCL	Upper confidence limit
USCS	Unified Soil Classification System
USGS	United States Geological Survey
VOC	Volatile organic compounds
WMC	Waste Management of Colorado



## ACRONYMS AND ABBREVIATIONS (cont'd)

WSDs	Work settling defendants
WTP	Water treatment plant

Draft for Public Review

## 1.0 Introduction and Purpose

This Conceptual Site Model (CSM) was completed for the Lowry Landfill Superfund Site (LLSS) in Arapahoe County, Colorado. A CSM is an illustrative summary of the key aspects of a site designed to help stakeholders visualize and understand available information. The primary purpose of a CSM is to portray the current understanding of geology, hydrogeology, contaminant sources, and transport pathways for a site. The utility of a CSM document changes depending on the phase of the Superfund process. The remedy for the LLSS is in the operations and maintenance (O&M) phase. Additionally, issues and recommendations for the site were identified in the 2017 Fourth Five Year Review, some of which relate to the development of an updated, comprehensive CSM document that benefits from recent additional characterization efforts taken at the site, including a site-wide contemporaneous sampling effort and resultant 3-dimensional data visualization and analysis (3DVA) of site data.

This CSM was completed to describe the current understanding of site conditions and communicate with site stakeholders. The CSM describes site features, the surface and subsurface conditions at LLSS, the nature and extent of identified contaminants of concern (COC) and the risk they pose to human health and the environment. This CSM was directed by the U.S. Environmental Protection Agency (EPA) Region 8 in response to findings and recommendations in the Fourth Five-Year Review (EPA 2017). EPA and the Lowry Landfill Work Settling Defendants (WSDs) agreed to collaborate on the development of the CSM. This CSM was completed jointly by Pacific Western Technologies (PWT) and Tetra Tech, Inc. (Tetra Tech) on behalf of EPA Region 8 and by CDM Smith on behalf of the WSDs.

The CSM was completed as part of EPA's emphasis on project life cycle CSMs (EPA 2011). A project life cycle CSM is a comprehensive graphical and written summary of what is known or hypothesized about environmental contamination at a site and the relationships among key site information that are pertinent to decision-making. A project life cycle CSM is comprised of six stages, as described below:

1. **Preliminary CSM Stage** – Site representation based on existing data; conducted prior to systematic planning efforts.
2. **Baseline CSM Stage** – Site representation used to gain stakeholder consensus or disagreement and identify data gaps and uncertainties; conducted as part of the systematic planning process.
3. **Characterization CSM Stage** – Continual updates to the CSM as new data or information is received during investigations; supports remedy decision making.
4. **Design CSM Stage** – Targeted updates to the CSM to support remedy design.
5. **Remediation/Mitigation CSM Stage** – Continual updates to the CSM during remedy implementation; provides the basis for demonstrating the attainment of cleanup objectives.
6. **Post Remedy CSM Stage** – Used to support reuse planning and placement of institutional controls (ICs) if warranted.

The LLSS is currently in the remediation/mitigation CSM stage. Remedies have been constructed to contain the landfill waste, landfill gas, surface water, soil, and groundwater. The WSDs perform ongoing O&M activities and report the results of the monitoring to EPA and the Colorado Department of Public Health and Environment (CDPHE) in the semiannual Remedial Action and Operations and Maintenance Status Reports, which are commonly referred to as the Site Status Reports (SSR).

This document summarizes historical data and reports, including Remedial Investigations (RI), the Record of Decision (ROD), Five-Year Reviews, and operation, maintenance, and monitoring status reports. The CSM also includes more recent data in response to recommendations in the 2017 Five Year Review. This CSM describes (1) the site location, history, and waste disposal practices; (2) the geology and hydrogeology; (3) the remedy components; (4) the nature and extent of contamination; (5) the fate and transport of the contamination; and (6) the potential risks to human health and the environment. Tables summarizing site data and figures and illustrations depicting CSM components follow each section of the text.

Draft for Public Review

## 2.0 Site Location and Setting

The LLSS is approximately 500 acres in western Arapahoe County, Colorado, 15 miles southeast of the City and County of Denver and one-half mile east of the City of Aurora. The LLSS is near the intersection of East Quincy Avenue and Gun Club Road (Figure 2-1). The LLSS is in Section 6, Township 5 South, Range 65 West and in the southern portion of Section 31, Township 4 South, Range 65 West. The North End study area extends approximately three miles north of the site and is coincident with the drainages of Murphy Creek and an unnamed creek east of East Toll Gate Creek (Figure 2-2).

From the mid-1960s until 1980, the City and County of Denver operated the landfill, which accepted liquid and solid municipal and industrial wastes, including sewage sludge disposed of in unlined pits or through land application. After 1980, waste disposal on site was restricted to municipal waste and later, to asbestos waste. Municipal solid waste disposal activities ceased in 1990 and a 4-foot cover was installed over the landfill unit. Asbestos disposal occurred northwest of the landfill and is ongoing northeast of the landfill (Figure 2-3). Landfilling operations contaminated soil, groundwater, surface water, and sediment with hazardous substances. Additionally, gases from buried wastes contaminated the air spaces in subsurface soil.

The Denver Arapahoe Disposal Site (DADS), an operating municipal solid waste landfill, forms the northern boundary of the LLSS (Figure 2-3). The City of Denver is the sole owner of the DADS parcels, which are operated by Waste Management of Colorado (WMC). DADS includes a closed, lined landfill in the western portion of Section 31, north of the site, which was constructed with a leachate collection system. This closed landfill is commonly referred to as the DADS landfill. Active landfilling operations continue on the northern portion of Section 32 and the northeastern portion of Section 31. The active landfills are lined and include leachate collection systems. Solid waste disposal operations are expected to continue at DADS for the next several decades. Landfill areas generate topographic highs readily discernible on the topographic contour maps (Figures 2-3 and 2-4). The site is currently fenced and WMC regularly patrols the fence. The main entrance to the site is a gate at the intersection of East Hampden Avenue and Gun Club Road. The gate is locked when DADS is not operating. DADS maintains a site office and truck water-loading area in the northwest portion of Section 6.

The site and surrounding areas are in gently rolling shortgrass prairie characteristic of the Great Plains physiographic province. Topography consists of gentle slopes on the north half of Section 6 and a topographic high on the south half of the section caused by past landfilling activities (Figure 2-3). Sections 31 and 32 (East Hampden Ave to Yale Ave), 30 (Yale Ave to East Jewell Ave), and 19 (East Jewell Ave to East Mississippi Ave) are in similar, gently rolling topography to the natural terrain in Section 6 (Figure 2-4). The 18-hole Murphy Creek Golf Course is located within Sections 30 and 19. Section 19 contains residential development throughout most of the section, surrounding the golf course areas (Figure 2-2). Land use in the general area surrounding the site is changing, with new and planned residential communities west and north of the site and DADS landfill.

The site is located within the Murphy Creek drainage system and includes an unnamed tributary (ephemeral creek) to Murphy Creek. Murphy Creek is located immediately east of the site and extends to the north of the site (Figure 2-4). The unnamed creek extends from the toe of the landfill through the northern portion of the site.

Many stream channels in the area surrounding the LLSS formed in response to subsidence during the Pennsylvanian Subperiod, Cretaceous /Tertiary Periods, and Miocene Epoch. The stream channels developed low sinuosity (bending) but were constrained by cohesive channel banks. Local subsidence occurred and topographically low areas filled with sands, silts, and clays (sub-cycles). Streambeds are typically incised about 5 feet into the topography. Illustration 2-1 provides a macro-scale presentation of the environmental systems in the area. The illustration provides general naming conventions for the water cycle, surface water, groundwater, and lithological deposits presented in this document. Many of these terms are also defined in footnotes throughout the document.

Streamflow on and near the site is ephemeral. Surface water in Murphy Creek and the unnamed creek typically consist of standing (i.e., non-flowing) water in scattered pools and puddles and only contain flowing water during significant precipitation or snow melt events. Thus, within the Murphy Creek and unnamed creek drainage systems there is no moving surface water and transport is limited to stormwater flow during or immediately after precipitation events. When flowing, the streams and tributaries generally flow northward. Groundwater discharge may occur to surface waters in some areas and times of year downgradient of the site. When flowing, Murphy Creek is likely a losing stream in that stormwater in the Murphy Creek drainage system is infiltrating into the subsurface beneath. Trees and shrubs, are common within and along the incised streambeds of Murphy Creek and unnamed creek because of the ready access to water not available in other areas.

A stormwater detention pond approximately 500,000 square feet in area is located between the closed and active cells of the DADS landfill, along the northern boundary of Section 31 (Figure 2-3). Aerial photographs of the area suggest that standing water is frequently, but not always, present within the detention pond. The detention pond likely contributes locally to groundwater recharge as a result of stormwater infiltration<sup>1</sup>. A leaching field and operations at the water truck loading facility located at the DADS office also may contribute localized groundwater recharge.

Precipitation, evapotranspiration<sup>2</sup>, and groundwater recharge and discharge are important components of the water budget for the site area. Most precipitation leaves the pond as surface water runoff, by evaporation and sublimation, or by evapotranspiration through grasses and vegetation, including large phreatophyte<sup>3</sup> trees (Illustration 2-1). Evapotranspiration at the streambeds is assumed to be a source of losses from the groundwater system. As a result, streambeds are likely to be local sinks for groundwater flow, and groundwater underflow is likely minimal across larger stream features.

Based on data collected from 1985 to 2015 at Buckley Air Force Base, the average annual precipitation is 7.28 inches per year and the wettest month is May with an average of 1.17 inches of precipitation (<https://www.timeanddate.com/weather/usa/aurora-co/climate>). Paschke (2011) cited evapotranspiration from groundwater as the primary process for natural discharge in the Denver Basin. At the site, more than 50 percent of the days in a given year are classified as clear, and the average

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<sup>1</sup> Infiltration is the process by which water on the ground surface enters the soil. If the precipitation rate exceeds the infiltration rate, surface runoff will usually occur unless there is a physical barrier.

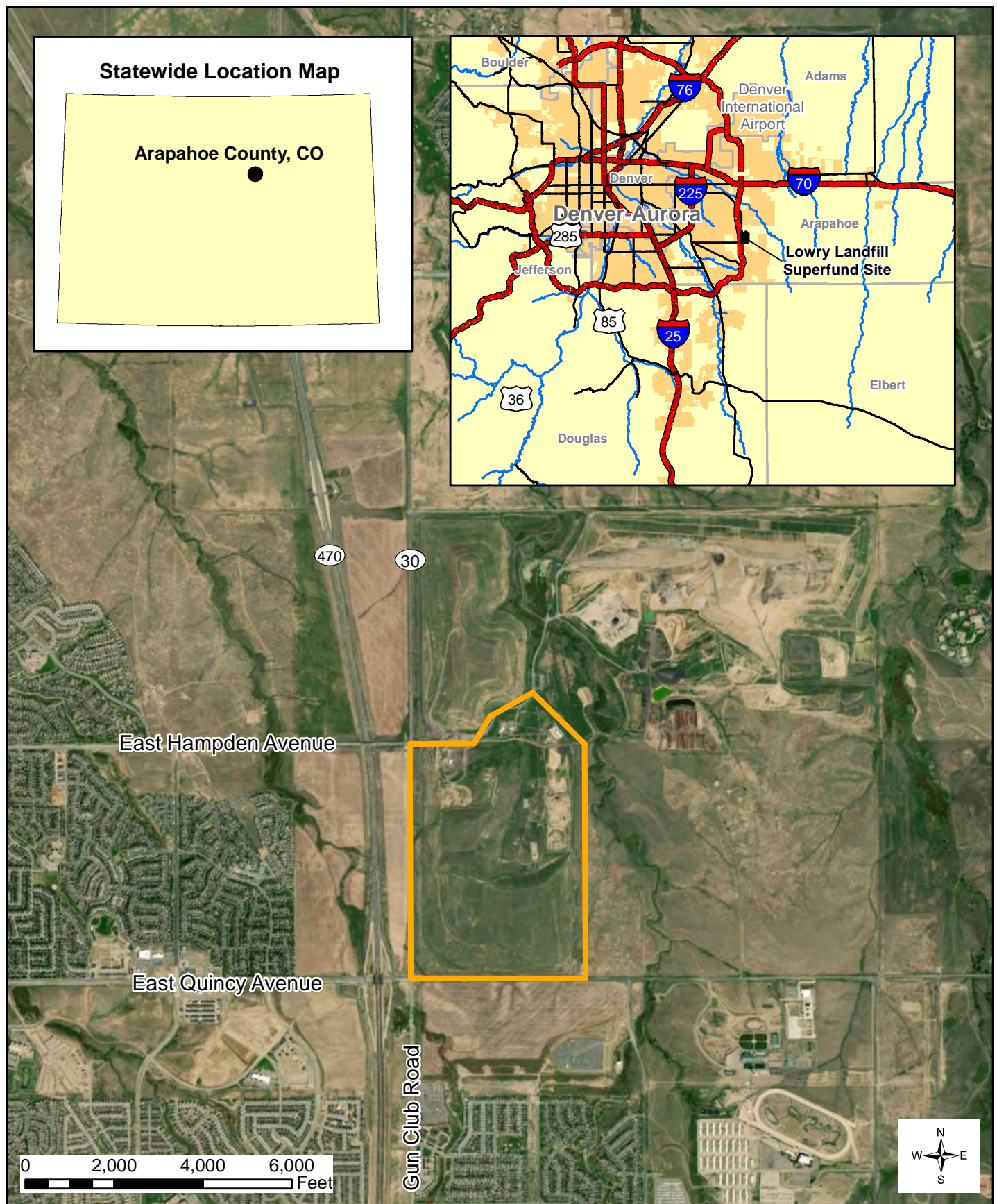
<sup>2</sup> Evapotranspiration is the combined effects of evaporation and plant transpiration to move water from the soil or other surface to the atmosphere. Transpiration is the movement of water through a plant and its evaporation from leaves, stems, or flowers.


<sup>3</sup> A phreatophyte is a deep-rooted plant that absorbs water from the groundwater or the soil directly above the groundwater table. Phreatophytes often have their roots constantly in touch with moisture.

humidity of the area is less than 50 percent. Evapotranspiration represents groundwater discharge from the water table to evapotranspiration in areas where the water table is shallow and phreatophytes, or plants that require a constant source of moisture, grow. Evapotranspiration rates in the range of 25 to 45 inches per year were used in USGS simulations along stream valley areas. According to Paschke (2011), estimated net recharge (precipitation recharge less evapotranspiration) is in the range of 0.5 to 2 inches per year.

Though likely infrequent in most areas of the site, when there is surface water in the intermittent stream beds of Murphy Creek and its tributaries (e.g., in response to temporal events such as rain storms or during periods of snowmelt), the surface water has the potential to contribute to groundwater recharge in some localized areas of the watershed during wet periods. Recharge in some areas, such as the off-site golf course and residential areas in the Murphy Creek subdivision near Mississippi Avenue, is likely greater than precipitation recharge alone, due to urban return flow, i.e., irrigation return and pipe leakage. Paschke (2011) estimated urban return flows at 2.5 inches per year in the Denver Basin. Conversely, engineered features such as landfill covers are designed to prevent or minimize precipitation recharge in localized areas. Engineered features that impact groundwater recharge are described in Section 5.0.





 Approximate Site Boundary

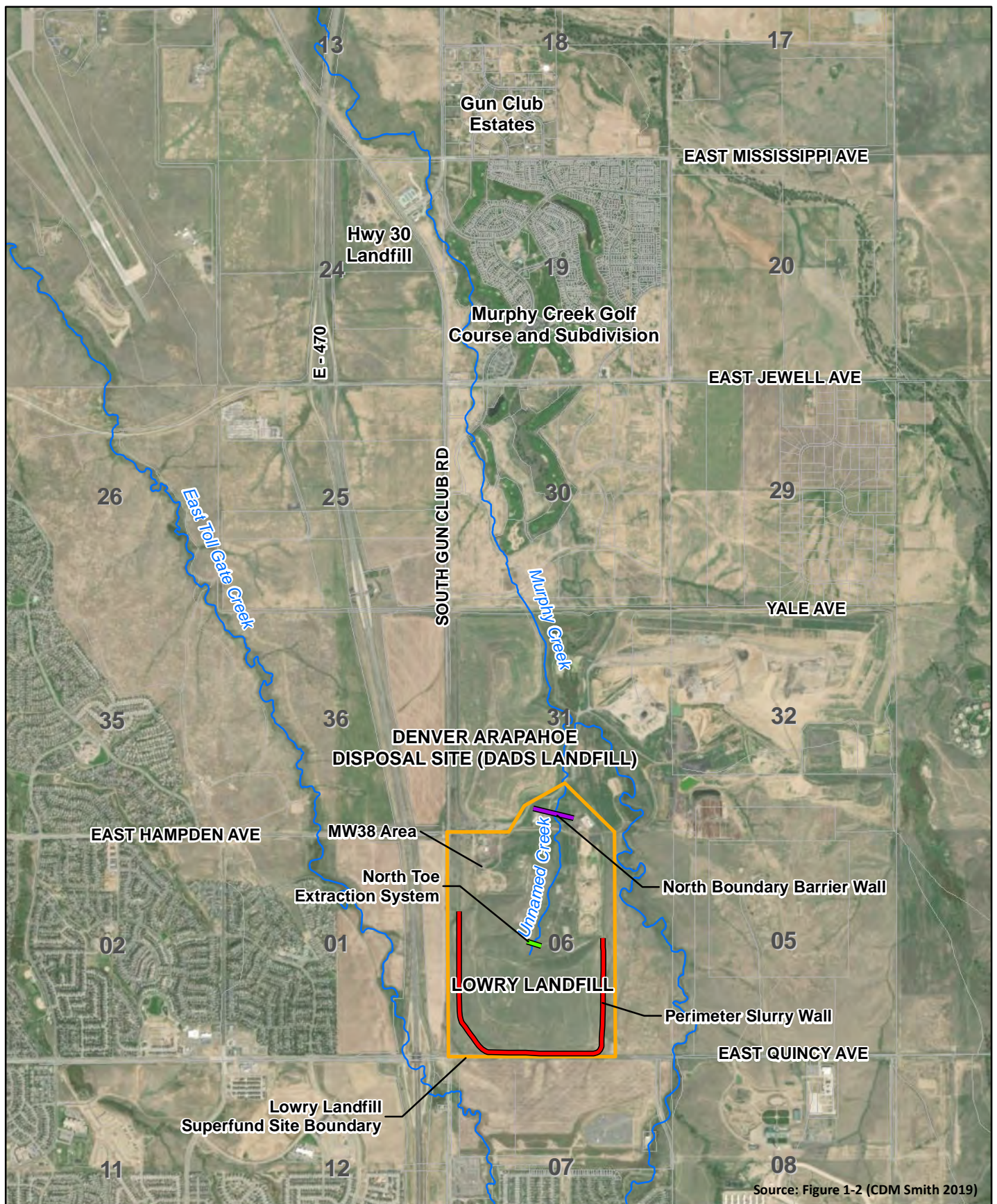
**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 2-1**  
**Site Location**

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Source: Figure C-1 (EPA 2017);  
Figure 1-1 (CDM Smith 2019)

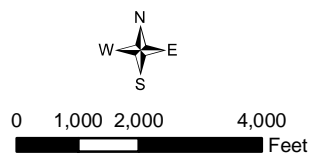




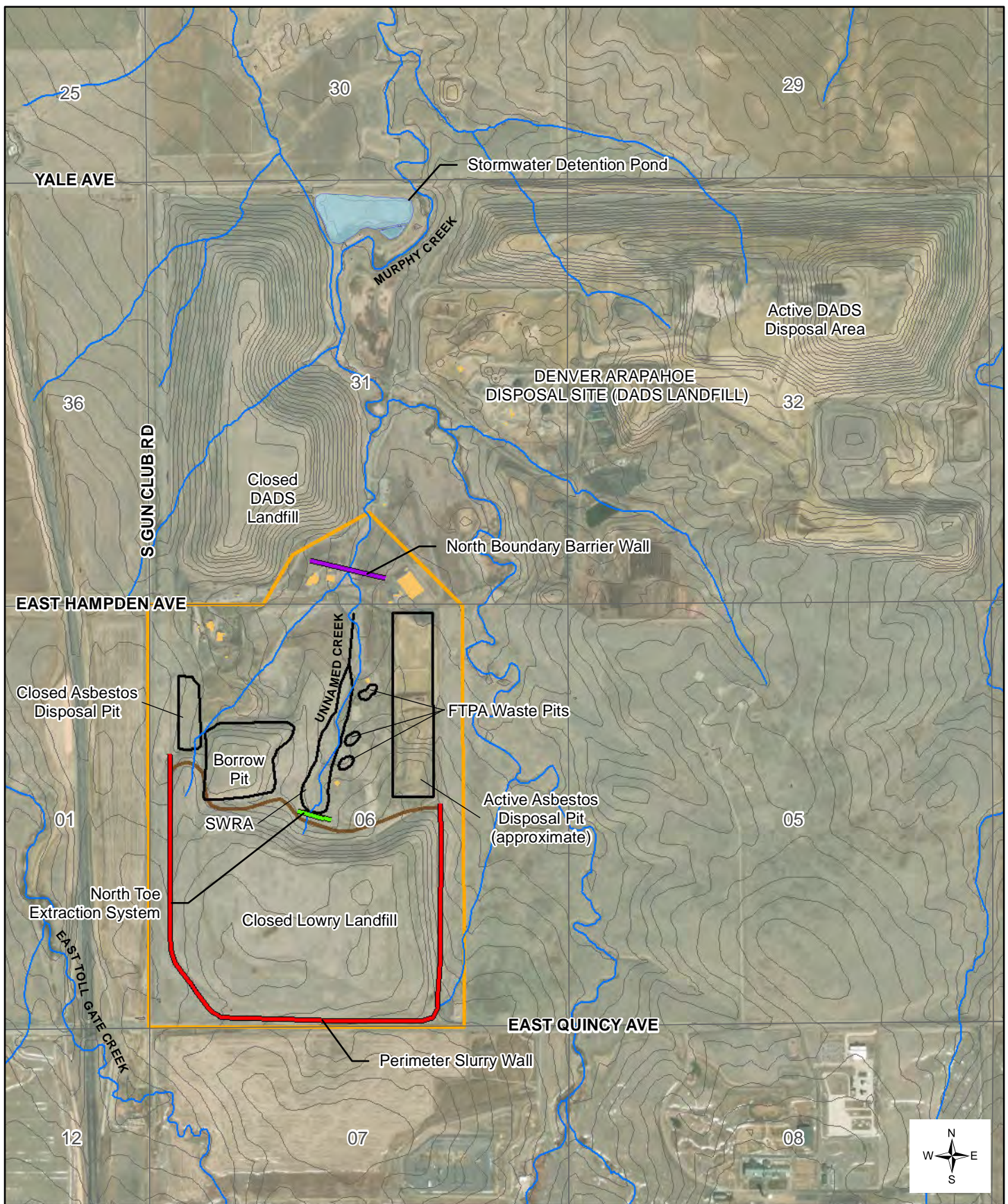
## LOWRY LANDFILL SUPERFUND SITE

Arapahoe County, Colorado

**Figure 2-2**  
**Site Features**







- North Boundary Barrier Wall
- Slurry Wall
- North Toe Extraction System
- Streams
- Detention Pond
- Site Boundary
- Buildings
- Topography Contour (10-ft Interval)

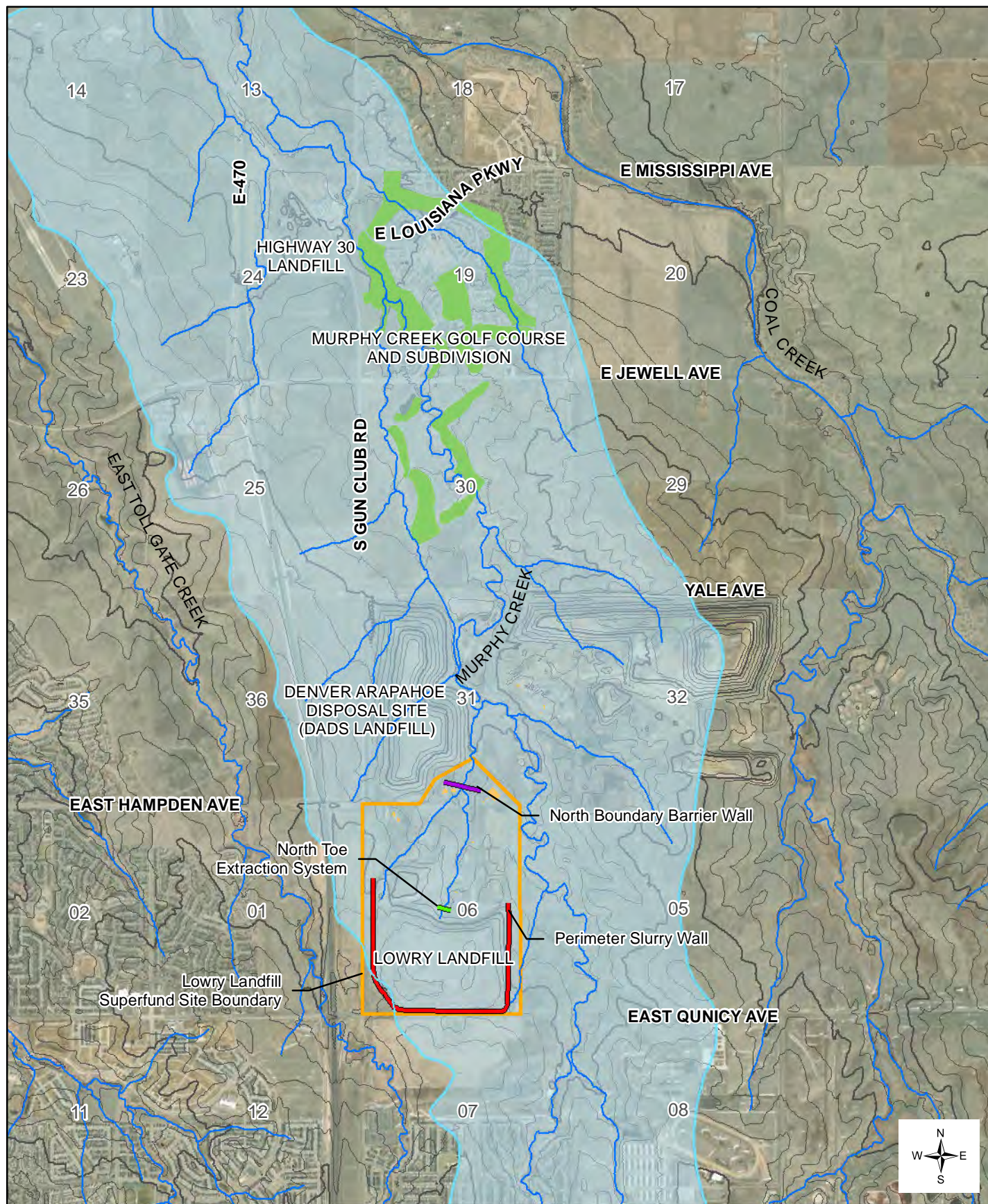
Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

Source: Figure 1 (EPA 2017);  
Figures 1-3 and 3-3 (CDM Smith 2019)

## LOWRY LANDFILL SUPERFUND SITE Arapahoe County, Colorado

**Figure 2-3  
Landfill Operation Areas**





- North Boundary Barrier Wall
- Slurry Wall
- North Toe Extraction System
- Streams
- Murphy Creek Drainage Area
- Golf Course
- Buildings
- Site Boundary
- Topography Contour (20-ft Interval)

Service Layer Credits: Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

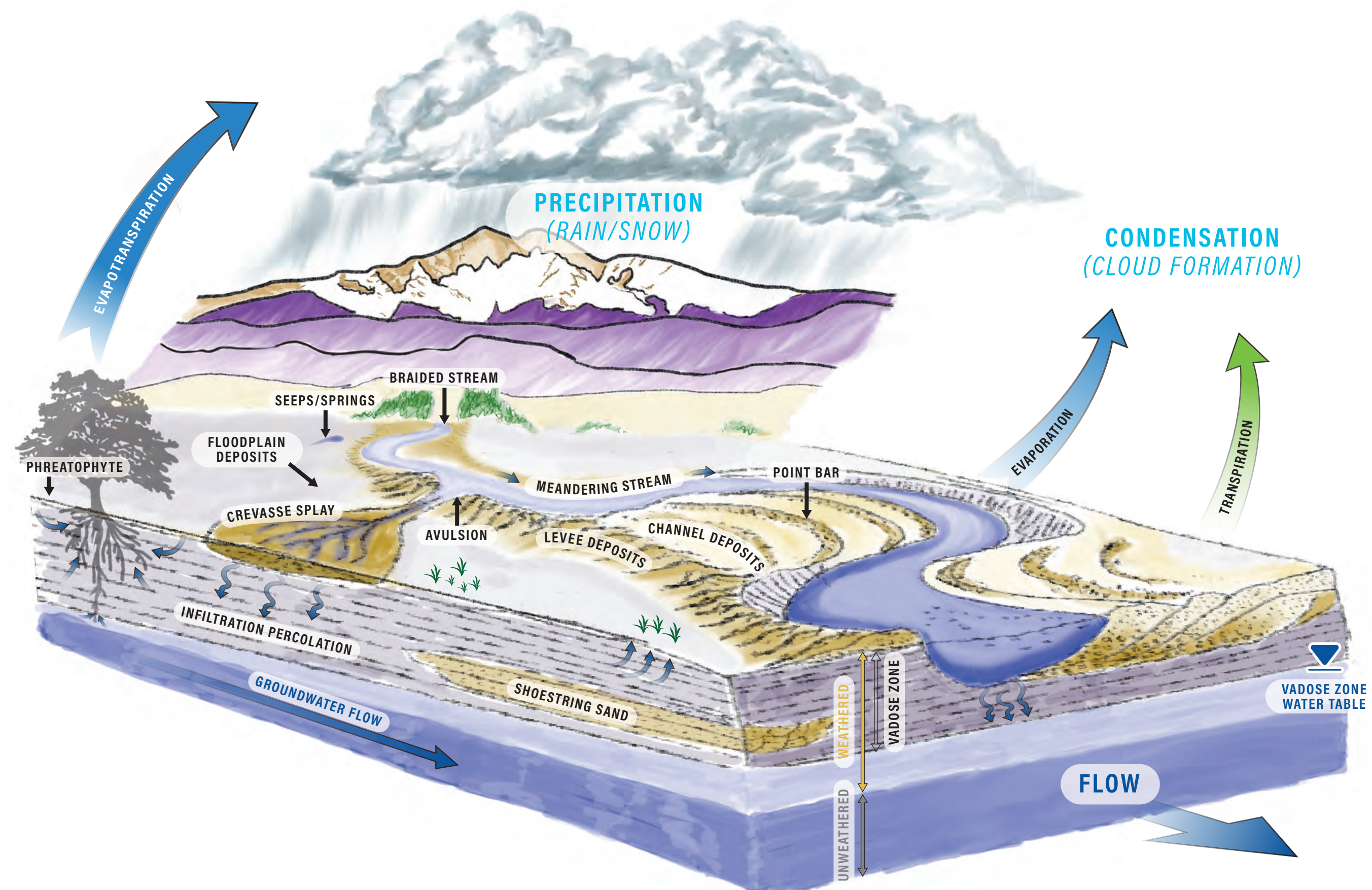
Source: Figure 3-2 (CDM Smith 2019)

## LOWRY LANDFILL SUPERFUND SITE Arapahoe County, Colorado

**Figure 2-4**  
**Area Topography and**  
**Murphy Creek Drainage**



# 2-1 Fluvial Deposition System



### 3.0 Site History and Contamination

This section describes the history of the LLSS, including waste disposal practices; previous investigations; COCs in soil, surface water, groundwater, and soil gas; and the remedial action objectives (RAO) identified for the site.

From 1966 until 1980, waste was disposed of at the Lowry Site, primarily by using a disposal practice known as “co-disposal.” Approximately 75 unlined waste pits or trenches were excavated to accommodate a mixture of liquids, industrial waste, and municipal waste; the pits and trenches located in early investigations are shown on Figure 3-1. Prior to 1976, the pits and trenches were filled about three-quarters full with liquid wastes and topped with 25 to 60 feet of municipal refuse. After 1976, the disposal technique was reversed and solid waste was placed first in the trenches, compacted, and then the trench or pit was filled with liquid waste. The disposal method was changed to promote more absorption of the liquids into the solid waste. The waste pits ranged in depth from approximately 15 to 30 feet, length from 100 to 1,100 feet, and width from 50 to 150 feet. Illustration 3-1 depicts two examples of the waste pits, one with refuse and liquid waste located above the groundwater table elevation (Illustration 3-1[a]) and one with waste below the groundwater elevation (Illustration 3-1[b]). No measures are known to have been implemented to prevent leachate<sup>4</sup> or liquid waste seepage from the pits. Consequently, over time, liquid seeped through the refuse and into the soil surrounding the pit. In some instances, the liquid or leachate migrated through the soil and impacted groundwater, creating a groundwater contaminant plume, as shown on the illustration. Similarly, in the north-central portion of Section 6, excavated pits were filled with liquid wastes and municipal refuse, then covered with 2 to 5 feet of native soil and piles of discarded tires. Over time, this liquid seeped out to groundwater and to surface water in the unnamed creek.

Land application of wastewater sludge began at the Lowry Site in 1969 and continued into 1986. Approximately 160 acres along the northern and eastern boundaries of Section 6 were utilized for land application of the wastewater sludge. The wastewater sludge was applied to the surface and then infiltrated into the native soils. After 1980, leachate that had been collected in on-site surface impoundments was injected into the subsurface in the same areas. The application of municipal sewage sludge and leachate contaminated the soil in this area. Figure 3-2 presents the potential sources of surface soil contamination.

The total volume of liquid wastes disposed of at the landfill is estimated to be 138 million gallons (EPA 1994). This estimate was developed from the records kept by the landfill and by the parties disposing of the wastes. The types of wastes disposed of at the Lowry Site until 1980 include acid and alkaline sludges; asbestos; caustic liquids and solids; brines including plating wastes and other water-based sludges; laboratory wastes; organics including petroleum-based oils, grease, chlorinated solvents, and sludges; waste solvents, chemicals, and oil; biomedical wastes; low-level radioactive medical wastes; pesticides and garden chemicals; water-soluble oils; sewage sludge; paint and varnish waste, sludge and thinners; photographic chemicals and industrial solvents; construction waste; municipal refuse; household hazardous waste; appliances; tires; livestock carcasses; and metallic wastes. In addition, approximately 6 to 10 million tires were stockpiled at the Lowry Site in the 1970s and 1980s.

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<sup>4</sup> Leachate is any liquid that, in the course of passing through waste material, extracts soluble or suspended solids, or any other component of the material through which it has passed.



WMC began landfill operations on July 30, 1980 under a contract with Denver. At that time, waste disposal in Section 6 was restricted to municipal refuse and, later, asbestos waste. Municipal solid waste disposal activities at Section 6 were discontinued in August of 1990. One area of Section 6 east of the landfill continues to receive asbestos waste, which is disposed of in sealed containers (Figure 2-3). Section 6 also contains shredded tires in a monofill<sup>5</sup> to the north of the landfill on the east side of the section (Figure 3-1), and construction wastes from the surface water removal action were disposed immediately north of the landfill and capped with low permeability soils (Engineering Science 1993). The active DADS cells in Sections 31 and 32 are currently being used for disposal of municipal solid waste (Figure 2-3).

Illustration 3-2 presents a depiction of refuse placed during operation of the landfill in Section 6. As shown, precipitation occurring during landfilling operations infiltrated into the refuse. Leachate could have been generated in the landfill mass depending on factors such as the volume of precipitation and the absorbency, porosity, and permeability of the refuse. Leachate would migrate downward until (1) the leachate becomes perched on a non-permeable soil layer; (2) the leachate dehydrates when the pore suction or surface tension of the refuse or soil is greater than the gravitational pull on the liquid; or (3) the leachate reaches groundwater and creates a nonaqueous-phase liquid (NAPL)<sup>6</sup> or dissolved plume. These migration pathways are shown on Illustration 3-2.

Preliminary site investigations began in the mid-1970s in response to complaints from nearby residents about odors, disposal practices, and health concerns. Various parties including United States Geological Survey (USGS), EPA, CDPHE, Denver, and WMC performed site studies before 1984 when the site was listed on the National Priorities List (NPL). These investigations included installation of groundwater monitoring wells, surface water and sediment sampling, air and soil gas monitoring, and surface geophysical surveys. Sitewide investigations were conducted from 1985 through 1989 to further evaluate the nature and extent of contamination at the site. A chronology of site events is listed on Table 3-1.

In 1984, the site was listed on the NPL. Prior to selecting a final remedy, the WSDs and EPA implemented interim actions at the site. In 1984, the City and County of Denver entered into an Administrative Order on Consent (AOC) with EPA for the design, construction, and operation of a groundwater control and treatment system at the northern boundary of the site, known as the North Boundary Barrier Wall (NBBW). That system was installed in 1984. Between 1989 and 1990, EPA conducted a drum removal action at the site that consisted of re-packaging and removing drums of highly contaminated liquids and solids. In 1990, all municipal solid waste landfill operations stopped and WMC constructed a soil cover over the 200-acre main landfill (Figure 2-3). In 1991, the City of Denver and WMC entered into an AOC with EPA to construct and operate a surface water removal action (SWRA) that consisted of upgrading the existing water treatment plant (WTP) and constructing a

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<sup>5</sup> A monofill is a disposal unit that contains only wastes bearing the same EPA hazardous waste identification or compatible wastes.

<sup>6</sup> Nonaqueous phase liquids (NAPL) are liquids that do not dissolve in or mix with water. NAPLs that are denser than water are called dense nonaqueous phase liquids (DNAPL) and will sink in water. NAPLs that are lighter than water are called light nonaqueous phase liquids (LNAPL) and will float on the surface of water. Because they do not dissolve in or mix with water, they generally flow separately from groundwater.

collection system within the unnamed creek to segregate contaminated groundwater from uncontaminated surface water. That system was completed in 1992.

To facilitate investigation and remedy evaluation, EPA divided the site into six operable units (OU) according to the media they address:

- OU1: Shallow groundwater and subsurface liquids
- OU2: Landfill solids
- OU3: Landfill gas
- OU4: Soils
- OU5: Surface water and sediments
- OU6: Deep groundwater

The RIs for each OU were completed in 1992 and 1993 (Harding Lawson Associates, Inc. [HLA] 1992, Hydro-Search, Inc. [HSI] and Camp Dresser & McKee, Inc [CDM] 1993, CDM 1993). The OUs were grouped and studied as follows: OUs 1 and 6, OUs 2 and 3, and OUs 4 and 5. The RIs identified COCs, evaluated the fate and transport of contamination, and assessed potential risks to human and ecological receptors. The COCs identified at the LLSS include volatile organic compounds (VOC), semi volatile organic compounds (SVOC), metals, pesticides, polychlorinated biphenyls (PCB), methane, and other gases. The COCs for each medium are listed on Table 3-2. The sources, nature and extent, and estimated volume of contamination for the OUs are described in Section 6.0. Contaminants have migrated from the waste pits and refuse and have contaminated the soil, groundwater, and soil gas. The fate and transport of the contamination is described in Section 7.0. The primary threats to human health and the environment were identified as exposure to landfill gas, waste pit liquids, drums, groundwater, and contaminated seepage in the former unnamed creek drainage. Other identified threats were from contaminated landfill solids, soils, sediments, and groundwater. Evaluations of potential risks to human health or the environment are described in Section 8.0.

In 1994, EPA and CDPHE signed the ROD that formally laid out the plan for addressing contamination at the LLSS (EPA 1994). The RAOs identified in the ROD are listed on Table 3-3. The ROD identified a sitewide remedy that included containment, collection, treatment, and monitoring. The ROD was amended in 2005; three Explanations of Significant Differences (ESD) were completed in 1995, 1997, and 2007; and five minor modifications to the ROD were completed in 1995, 1996, 2001, 2002, and 2006 to reflect new information and minor remedy changes (EPA 1995a, 1995b, 1996, 1997, 2001a, 2002b, 2005d, 2006, 2007b). None of the changes fundamentally altered the sitewide containment remedy.

The site's long-term remedy uses containment, collection, treatment, and monitoring to address contamination. Remedy components include a slurry wall, landfill cover, the North Toe Extraction System (NTES), the NBBW, the SWRA, landfill gas removal with conversion to usable energy, removal of waste pits, long-term monitoring, and ICs. The remedy components are described in Section 5.0 and shown on Figure 3-3. In the ROD, EPA established numerical performance standards and points of compliance (POC) for the landfill gas remedy and the groundwater remedy at locations inside the site boundaries. The landfill gas (LFG) and groundwater compliance boundaries are shown on Figure 3-3. If performance standards are not met during implementation and operation, the remedy requires appropriate contingency measures to be implemented. The site's remedy is currently in the long-term O&M stage.



1,4-dioxane has been detected in groundwater north of the compliance boundary and was discovered in groundwater after the NBBW system was constructed. Before 2001, groundwater extracted from the NBBW area was treated with air stripping and granular activated carbon (GAC), and reinjected downgradient (north) of the NBBW through the injection trench or wells. Air stripping and GAC remove most VOCs but do not remove 1,4-dioxane. When 1,4-dioxane was identified as a COC, treatment to remove it became necessary. Consequently, in 2001, the groundwater treatment process was upgraded for its removal. That upgrade also involved discharging treated water to an off-site publicly owned treatment works (POTW), instead of reinjecting it north of the NBBW. A biological treatment system (BTS) was added to the on-site WTP in 2004 to treat NTES groundwater containing 1,4-dioxane. From 2001 through 2018, potable water was injected through the injection trench and wells to augment water rights for extracted groundwater, maintain containment at the NBBW, and flush residual contamination from the soil north of the NBBW. The injection of potable water was not a formal component of the remedy as described in the ROD and potable water injection ceased in 2018 in response to the recommendations in the 2017 Fourth Five Year Review (EPA 2017).

Starting in 2002, the lateral and vertical limits of 1,4-dioxane in groundwater downgradient of the NBBW were investigated. Comprehensive sampling programs were conducted in 2006 and 2007 to further evaluate the 1,4-dioxane concentrations downgradient of the NBBW, including off site to the north in Sections 31, 30, 24, and 19. Results of these investigations showed that 1,4-dioxane occurred above its performance standard in the NBBW area and in a groundwater plume extending from the site to more than 2 miles downgradient (north). Based on the discovery of 1,4-dioxane during the investigations, the WSDs implemented the North End response actions as a contingency measure on site and north of the site boundary. Extraction wells and associated collection piping were installed in five extraction areas (Areas 1 through 5). The objectives of the North End response actions were to reduce off-site migration of 1,4-dioxane, reduce the mass of 1,4-dioxane north of the site, and to bring into compliance any compliance monitoring well with concentrations above the performance standard. The extent of 1,4-dioxane north of the site, as detected in 2018, is shown on Figure 3-4.

The Fourth Five-Year Review for the site was completed in September 2017 (EPA 2017). Several of the issues and recommendations identified by EPA related to the migration of 1,4-dioxane off-site to the north. The Five-Year Review recommended development of an updated plume map and CSM, and further delineation of the 1,4-dioxane plume. The Five-Year Review also recommended cessation of the injection of potable water north of the NBBW. Injection of potable water ceased on October 2, 2018. The WSDs conducted a study to assess changes in groundwater elevations, capture zones, and groundwater chemistry resulting from the cessation of potable water injection (Engineering Management Support, Inc. [EMSI] 2019). Further monitoring of the effects of the cessation of potable water injection is ongoing.

**Table 3-1. Chronology of Site Events**

<b>Event</b>	<b>Date</b>
The City of Denver purchased 60,000 acres southeast of Denver and deeded the land to the federal government.	1939
Denver operated Lowry Landfill as a municipal and industrial landfill. The landfill accepted a variety of wastes, including liquid and solid industrial wastes, miscellaneous radioactive wastes, and sewage sludge.	1965-1980
Citizens issued complaints to regulatory authorities regarding odors, fires, and conditions of disposal practices causing spread of contamination to the surrounding area and to groundwater. EPA, the Colorado Department of Health, and Denver engaged in an ongoing process to identify contamination problems and modify operational practices.	1971-1979
Various investigations were conducted by EPA, the USGS, and the CDPHE and were performed by Denver and WMC.	Mid-1970s-1984
WMC took over the operation of the landfill under a contract with Denver. The landfill did not accept industrial waste and accepted only municipal refuse.	1980
EPA conducted a Preliminary Assessment for the Lowry Landfill.	June 1, 1980
EPA conducted a Site Inspection.	August 1, 1982
Lowry Landfill placed on the NPL.	September 21, 1984
Denver implemented an interim remedial measure consisting of a subsurface groundwater drain backed by a compacted clay barrier wall (the NBBW) and a WTP. EPA issued a Community Relations Plan for the Site.	1984
EPA conducted the Phase I RI.	1985-1986
The Agency for Toxic Substances and Disease Registry (ATSDR) completed a public health assessment of the Site.	1987
EPA conducted Phase II RI and designated OUs	1987-1989
EPA completed an Engineering Evaluation/Cost Analysis (EE/CA) of alternatives for the SWRA.	1988
EPA conducted the Drum Removal Action.	1989-1990
Municipal solid waste disposal activities in Section 6 were discontinued.	1990
Denver and WMC implemented a tire-shredding operation to shred approximately 8 million tires stockpiled in Section 6.	1989-1992

Event	Date
Potentially Responsible Parties (PRP) comprising the Lowry Coalition performed the RI for OUs 1 and 6.	1991-1992
The RI for OUs 2 and 3 was performed by Denver, WMC, Chemical Waste Management, Inc. (CWM) and the RI for OUs 4 and 5 was performed by Metro Wastewater Reclamation District [Metro] and Denver.	1992-1993
The Feasibility Study (FS) for OUs 1 and 6 was performed by the Lowry Coalition; the FS for OUs 2 and 3 was performed by Denver, WMC, CWM; and the FS for OUs 4 and 5 was performed by Metro and Denver.	1992-1993
Construction of the SWRA was completed.	1992
The Scrap Tire Removal Project was completed.	1993
EPA issued the Proposed Plans for OUs 1 and 6, 2 and 3, and 4 and 5.	1992-1993
EPA issued the ROD.	March 10, 1994
EPA issued the Unilateral Administrative Order (UAO) for Remedial Design/Remedial Action (RD/RA) to 34 PRPs. Respondents Denver, WMC, and CWM agreed to perform the RD/RA on behalf of themselves and 31 other PRPs.	November 18, 1994
EPA issued a minor modification to the ROD, which clarified ICs and allowed ongoing waste disposal activities.	1995
EPA issued the first ESD for the ROD, which clarifies performance standard criteria and modified the groundwater Point of Action (POA) boundary referenced in ROD to mimic the groundwater POC boundary along eastern, western, southern sides of the landfill mass, and along length of NBBW.	1995
EPA issued a minor modification to the ROD to clarify the wetland construction methodology.	1996
Respondents constructed the Landfill Gas Collection and Treatment System.	1996
EPA issued the second ESD, which allowed on-site disposal of contaminated materials from the Former Tire Pile Area (FTPA), and piping pretreated groundwater to Metro and the City of Aurora's Sand Creek Wastewater Reclamation facility.	1997
Respondents completed the NTES and East/South/West Barrier Wall.	1998
Respondents completed FTPA Middle Waste Pit excavation.	1999
Respondents completed the FTPA Middle Waste Pit treatment cell.	1999

Event	Date
Respondents completed North Face Landfill Cover.	1999
Respondents completed the new WTP.	2000
EPA conducted the First Five-Year Review.	2000-2001
EPA issued a minor modification to the ROD, changing the 1,1-dichloroethene air quality performance standard.	2001
Potable water injection started at the NBBW	2001
EPA issued a minor modification to the ROD to modify the performance standards based on new toxicity criteria and adding 1,4-dioxane as a COC.	2002
EPA issued the first Addendum to the First Five-Year Review.	2003
1,4-dioxane was detected in shallow groundwater north of the site. Investigations and monitoring began, and monitoring wells were installed.	2003-Present
Respondents constructed the BTS at the WTP.	2004-2005
Groundwater extracted from the NTES is treated in the upgraded WTP.	2005-Present
EPA approved the Site-wide Groundwater Monitoring Plan (GWMP).	2005
EPA approved the Work Plan for Additional Geologic Characterization of Potential Lineaments (as amended).	2005
Respondents implemented the MW-38 Area Gradient Control Contingency Measure.	2005
EPA issued the ROD Amendment for FTPA remedy.	2005
EPA certified the completion of construction of groundwater monitoring network.	2005
EPA certified completion of Remedial Action for the SWRA, MW38 Area Gradient Control Contingency Measure, and New Water Treatment Plant.	2005
EPA certified completion of work for the wetlands mitigation.	2005
EPA approved the Final Interim Closeout Report, Middle Waste Pit Remediation and Construction of the Treatment Cell, FTPA Waste Pit Remedy.	2005
United States entered into a consent decree with Denver, WMC, and CWM (WSDs), and five other responsible parties for recovery of the United States' costs and performance of remaining work at the Site.	2005
EPA established a new groundwater performance standard for 1,4-dioxane.	2006

Event	Date
EPA issued a minor modification to the ROD to designate a Corrective Action Management Unit for the disposal of treated FTPA soils	2006
EPA certified construction completion for site-wide remedy.	2006
EPA conducted the Second Five-Year Review.	2007
EPA issued the third ESD modifying the treatment component of the landfill gas remedy by adding a new on-site landfill gas-to-energy facility.	2007
EPA certified completion of Interim Remedial Action for the Groundwater Monitoring Program (EPA 2007c)	2007
WSDs installed wells to remove and treat 1,4-dioxane in groundwater north of the site.	2007-Present
EPA approved the Final Remedial Action Completion Report for the South Waste Pit portion of the FTPA.	2010
EPA approved Addendum 1 to the Final Construction Closeout Report for the gas-to-energy plant (GTEP).	2011
EPA completed the Third Five-Year Review.	2012
EPA approved Addendum 4 to the Final O&M Manual for the WTP.	2012
EPA approved completion of Final Remedial Action Report for North Waste Pit and FTPA.	2013
EPA approved Revision 2, Updated Compliance Monitoring Plan, LFG Remedy with updated subsurface gas performance standards.	2015
EPA completed the Fourth Five-Year Review.	September 2017
WSDs completed the most recent survey of private wells within 5 miles of the site.	2017
WSDs provided a progress report on the Assessment of Northern Extent of 1,4 – dioxane in groundwater north of well MW 144-WD.	2017
WSDs updated the Site Management Plan.	2018
EPA approved Revision 3, Updated Compliance Monitoring Plan, LFG Remedy with updated subsurface gas performance standards.	2018
EPA approved Revision 2 of the Groundwater Monitoring Plan.	2018
WSDs updated the Contingency Plan.	2018
WSDs completed the groundwater synoptic sampling event.	2018-2019

Event	Date
WSDs expanded WTP capacity and installed a larger discharge pipe. The WTP O&M manual was updated to reflect the upgrades.	2018-2019
WSDs conducted a pilot-test to cease potable water injection north of the NBBW and prepared periodic monitoring reports to study the effect of the cessation on the NBBW. EPA approved Final Cessation and Pilot-Test Report (EMSI and CDM Smith 2020a). Potable water injection ceased on October 2, 2018.	2018-2020
Addendum 6 of the O&M Manual for the Water Treatment Plant was completed.	2019
WSDs completed the North End investigation to assess the nature and extent of 1,4-dioxane in groundwater north of the NBBW to just north of East Mississippi Avenue.	2019 - 2020
WSDs completed the most recent annual evaluation and update to the practical quantitation limits (PQLs) as required by the Consent Decree.	2019
EPA certified for use the Calibrated Numerical Three-Dimensional, Finite-Element Groundwater Simulation Model.	2019
The Community Involvement Plan was updated.	2020
EPA and CDPHE completed a Risk Assessment called the 1,4-Dioxane Risk Summary - North End Sampling.	2020
EPA approved Technical Memorandum, Identification and Sampling of Water Supply Wells Within and Immediately Adjacent to Off-Site 1,4-Dioxane Plume.	2020
The Waste Management Plan, Remedial Action and Operations Manual was updated.	2020
EPA completed 3DVA of geology, hydrogeology, and chemistry.	2020
WSDs began extraction of groundwater from NBBW-IW-3 in the B-326/MW-113 area north of the NBBW.	2020
WSDs completed the North End Groundwater Monitoring Plan - Update 2	2020
EPA approved the NBBW Containment System Evaluation Plan.	2020
WSDs completed a report on molybdenum.	2020
WSDs completed the most recent annual evaluation and update to the PQLs as required by the Consent Decree.	2020

Event	Date
EPA approved Effectiveness Evaluation for Perimeter Barrier Wall, 2017 Five-Year Review Issue #3.	2021
EPA approved Effectiveness Evaluations for MW38 Area, NTES, and the North End Response Actions, 2017 Five-Year Review Issue #3.	2021
EPA signed the Five-Year Review Addendum.	2021
Landfill Gas Compliance Monitoring Plan, Landfill Gas Remedy was completed.	2021
EPA, in collaboration with the WSDs, developed the Site's CSM.	2019-2021
WSDs are conducting a Containment System Evaluation and Optimization Study for the NBBW.	Ongoing



**Table 3-2. Contaminants of Concern**

<b>Landfill Gas</b>			
1,1,1-Trichloroethane	2-Methylnaphthalene	Chloroform	PCBs
1,1,2,2-Tetrachloroethane	Acetone	Chloromethane	Pentachlorophenol
1,1,2-Trichloroethane	Acrylonitrile	Chromium	Phenol
1,1-Dichloroethane	Aniline	cis-1,2-Dichloroethene	Selenium
1,1-Dichloroethene	Arsenic	Dieldrin	Styrene
1,2,4-Trichlorobenzene	Barium	Dioxins/furans	Tetrachloroethene (PCE)
1,2-Dichlorobenzene	Benzene	Ethylbenzene	Toluene
1,2-Dichloroethane (DCA)	Beryllium	Gamma BHC	trans-1,2-Dichloroethene
1,2-Dichloropropane	Cadmium	Heptachlor	Trichloroethene (TCE)
1,4-Dichlorobenzene	Carbon disulfide	Lead	Vanadium
1-Butanone	Carbon tetrachloride	Manganese	Vinyl Chloride
4,4-Dichlorodiphenyltrichloroethane	Chlorobenzene	Methylene chloride	Xylenes
2-Hexanone	Chloroethane	Nickel	
<b>Subsurface Gas</b>			
1,1,1-Trichloroethane	2-Butanone	Ethylbenzene	Xylenes
1,1-DCA	Benzene	Methane	Vinyl Chloride
1,1-Dichloroethene	Carbon Disulfide	Methylene chloride	
1,2-DCA	Chloroform	Toluene	
<b>Groundwater</b>			
1,1,1-Trichloroethane	Acetone	Chloroform	Nitrite
1,1,2,2-Tetrachloroethane	Arsenic	cis-1,2-Dichloroethene	PCE
1,1,2-Trichloroethane	Benzene	Dibromochloromethane	Toluene
1,1-DCA	Bromodichloromethane (BDCM)	Ethylbenzene	trans-1,2-Dichloroethene
1,1-Dichloroethene	Bromoform	Iron	TCE
1,2-DCA	Cadmium	Methylene chloride	Vinyl chloride
1,2-Dichloropropane	Carbon tetrachloride	Naphthalene	

1,4-Dioxane

Chlorobenzene

Nitrate

**Surface Soil and Surface Water**

2,3,7,8-Tetrachlorodibenzodioxin

Cadmium

Cyanide

PCB-1260 (Aroclor-1260)

Aluminum

Chloroform

Lead

Silver

Arsenic

Chromium

Manganese

Toluene

Barium

Cobalt

Mercury

Vanadium

Beryllium

Copper

Nickel

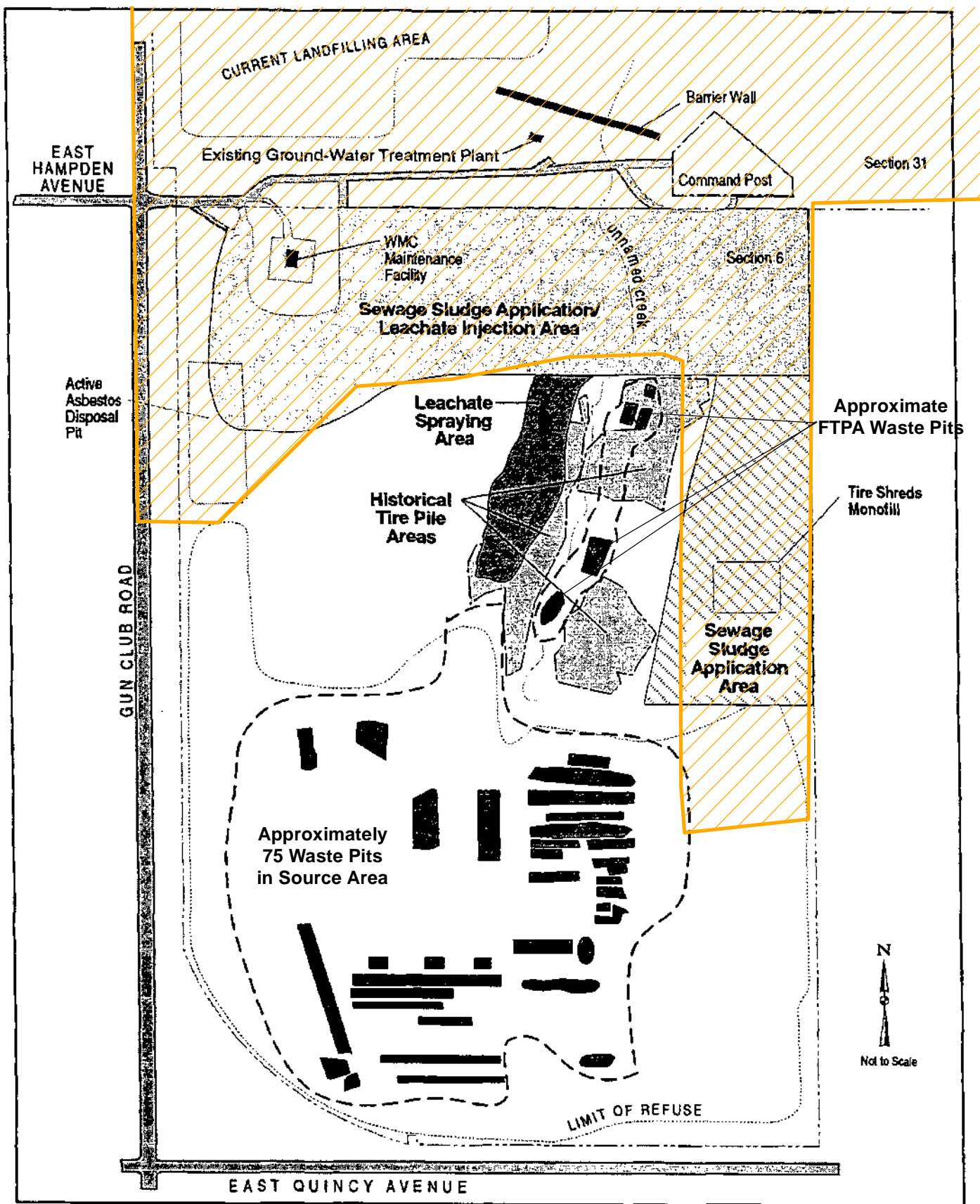
Zinc

**Table 3-3. Remedial Action Objectives**

<b>Groundwater</b>
<ul style="list-style-type: none"><li>• Prevention of exposure to humans and the environment (through ingestion, inhalation, or dermal absorption) from liquids (either groundwater or waste-pit liquids) containing contaminants in excess of the performance standards</li><li>• Prevention of migration of contaminants beyond the compliance boundary in excess of the performance standards</li><li>• Prevention of horizontal migration of dissolved groundwater contaminants off-Site and to surface waters</li><li>• Prevention of vertical migration of dissolved groundwater contaminants beyond the lignite layer</li><li>• Prevention of movement of NAPLs beyond the compliance boundary and minimization of movement of NAPLs</li><li>• Minimization of infiltration and leachate production in waste-pit source area</li></ul>
<b>Landfill Solids</b>
<ul style="list-style-type: none"><li>• Protection of human health and the environment from direct contact or ingestion of landfill solids or soils intermingled with landfill solids containing contaminants</li><li>• Protection of humans from inhalation of volatilized contaminants from landfill solids or soils intermingled with landfill solids, and inhalation of contaminated airborne particulate matter from soils or landfill solids that exceed performance standards</li><li>• Minimization of the production and migration of leachate, from landfill solids or soils intermingled with landfill solids, to the saturated zone and groundwater</li><li>• Minimization of the migration of soils intermingled with solids, caused by erosion or entrainment by wind or water</li><li>• Prevention of off-site migration of landfill solids and soils intermingled with solids into other media</li><li>• Protection of human health and the environment from direct contact with or ingestion of leachate that exceeds the performance standards for shallow groundwater and subsurface liquids</li><li>• Prevention of off-site migration of leachate or infiltration into other media</li></ul>
<b>Landfill Gas</b>
<ul style="list-style-type: none"><li>• Protection of human health from inhalation of landfill gases in excess of the performance standards</li><li>• Protection of human health and the environment from explosion hazards associated with landfill gases</li><li>• Prevention of off-site migration of landfill gas or migration to other media</li></ul>
<b>Soils, Surface Water and Sediments</b>
<ul style="list-style-type: none"><li>• Protection of human health and the environment from direct contact or ingestion of soils, surface water, and sediments containing contaminants that exceed the performance standards</li><li>• Protection of human health from inhalation of volatilized contaminants from the soils, surface water, or sediments; and inhalation of contaminated airborne particulate matter from soils or sediments that exceeds performance standards</li></ul>

- Minimization of the production and migration of contaminated surface water to the saturated zone and groundwater
- Minimization of the migration of soils and sediments by erosion or entrainment by wind or water
- Minimization of migration of contaminated surface water off-site and into other media

Draft for Public Review



**LEGEND:**

- Area of Waste Pit Containing Liquids
- Boundary of Area of Suspected Liquid Waste Pits (Source Area)
- Landfill Boundary (Fence Line)
- Former Landfill Boundary
- Sludge - spreading area\*

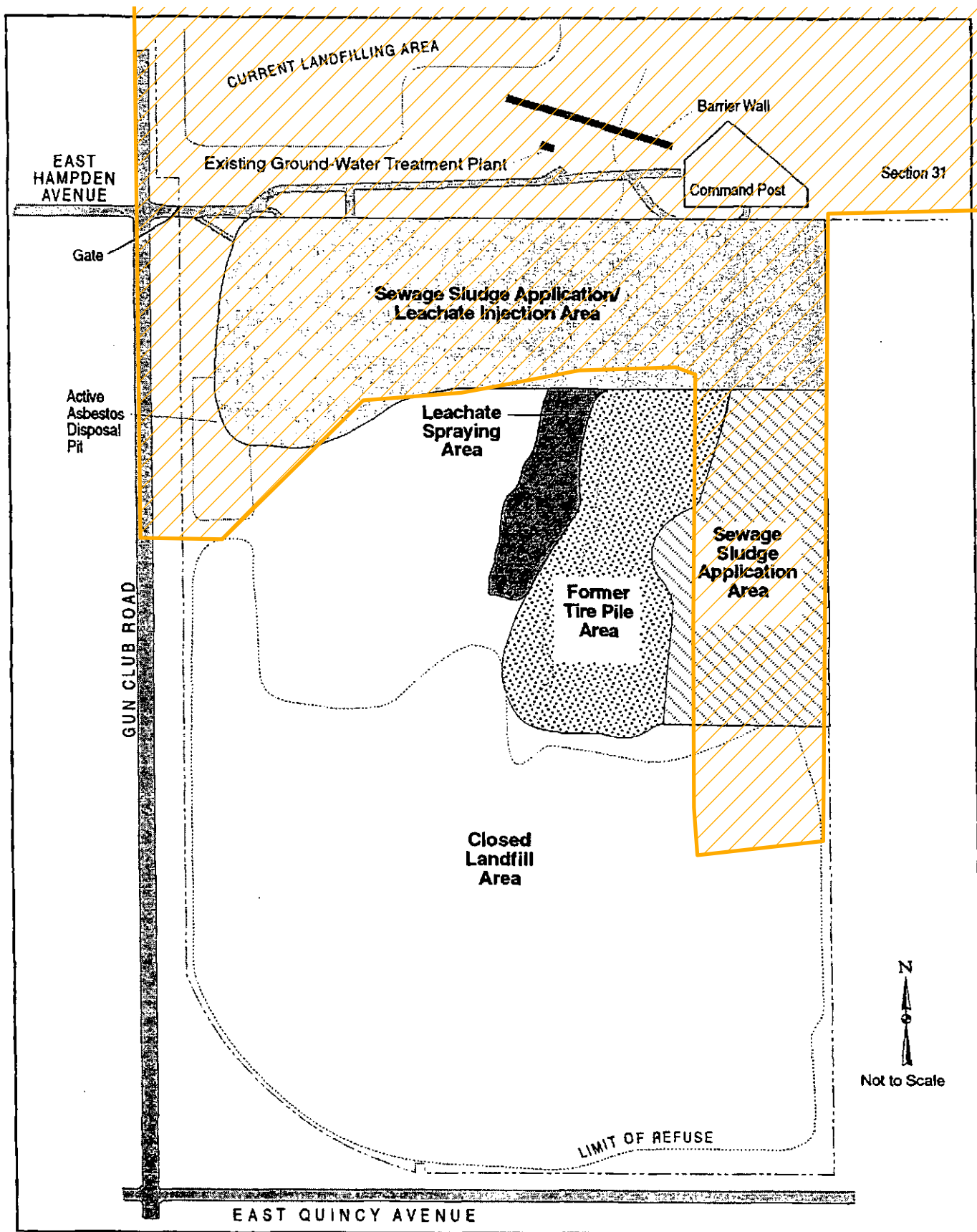
The locations shown are approximate.

Circa 1980 - 1986


Source: Figure 3-1 (ROD)

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 3-1**  
**Approximate Waste Pit, Tires, and**  
**Sludge Application Area Locations**



**LEGEND:**

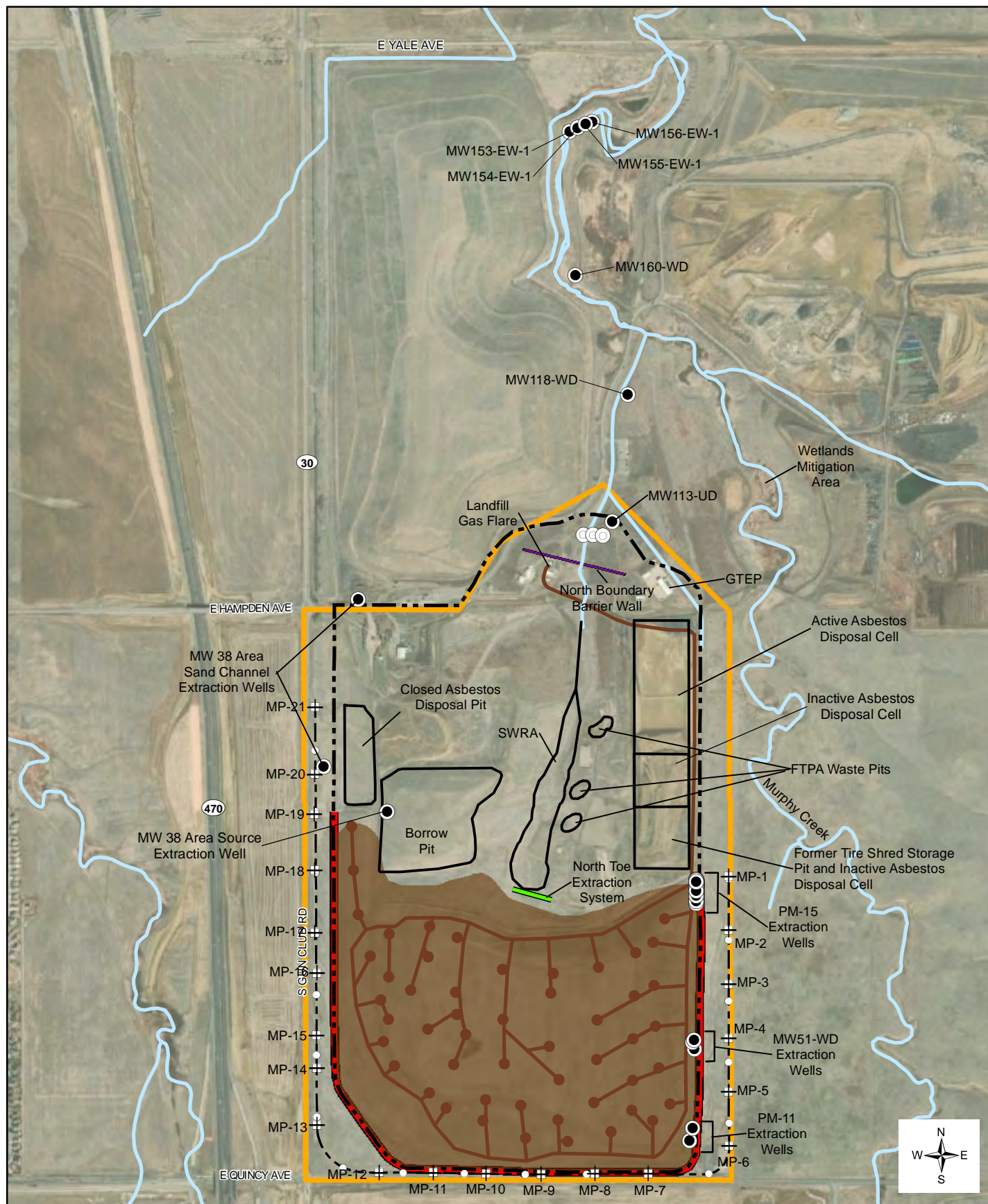
- Landfill Boundary (Fence Line)      Circa 1980 - 1986
-  Sludge - spreading area\*
- The locations shown are approximate.

Source: Figure 6-6 (ROD)

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 3-2**  
**Potential Sources of**  
**Surface Soil Contamination**





- |                                 |                                      |
|---------------------------------|--------------------------------------|
| Approximate Site Boundary       | Landfill Cover                       |
| Groundwater Compliance Boundary | Landfill Gas Extraction Lines        |
| LFG Compliance Boundary         | Former Potable Injection Wells       |
| Slurry Wall                     | Voluntary Actions Extraction Systems |
|                                 | LFG Monitoring Point                 |

Source: Figure 1 (EPA 2017); Figure 1-3 (CDM Smith 2019); Figure 5.1 (Parsons 2014)

## LOWRY LANDFILL SUPERFUND SITE Arapahoe County, Colorado

**Figure 3-3  
Remedy Components**





Existing Wells

- Shallow Well
- Deep Well

Plume

- 1,4-Dioxane concentration greater than site's performance standard of 0.9 µg/L using most recent sample results (dashed where inferred)
- Lowry Landfill Superfund Site Boundary

Notes:

- MW179-UDEN** - wells sampled during North End Investigation
- MW129-WD** - wells sampled during the 2018 Synoptic Event

0 1,000 2,000 3,000 Feet

Source: Figure 4.1 Phase 1 Technical Memorandum (North End Report)

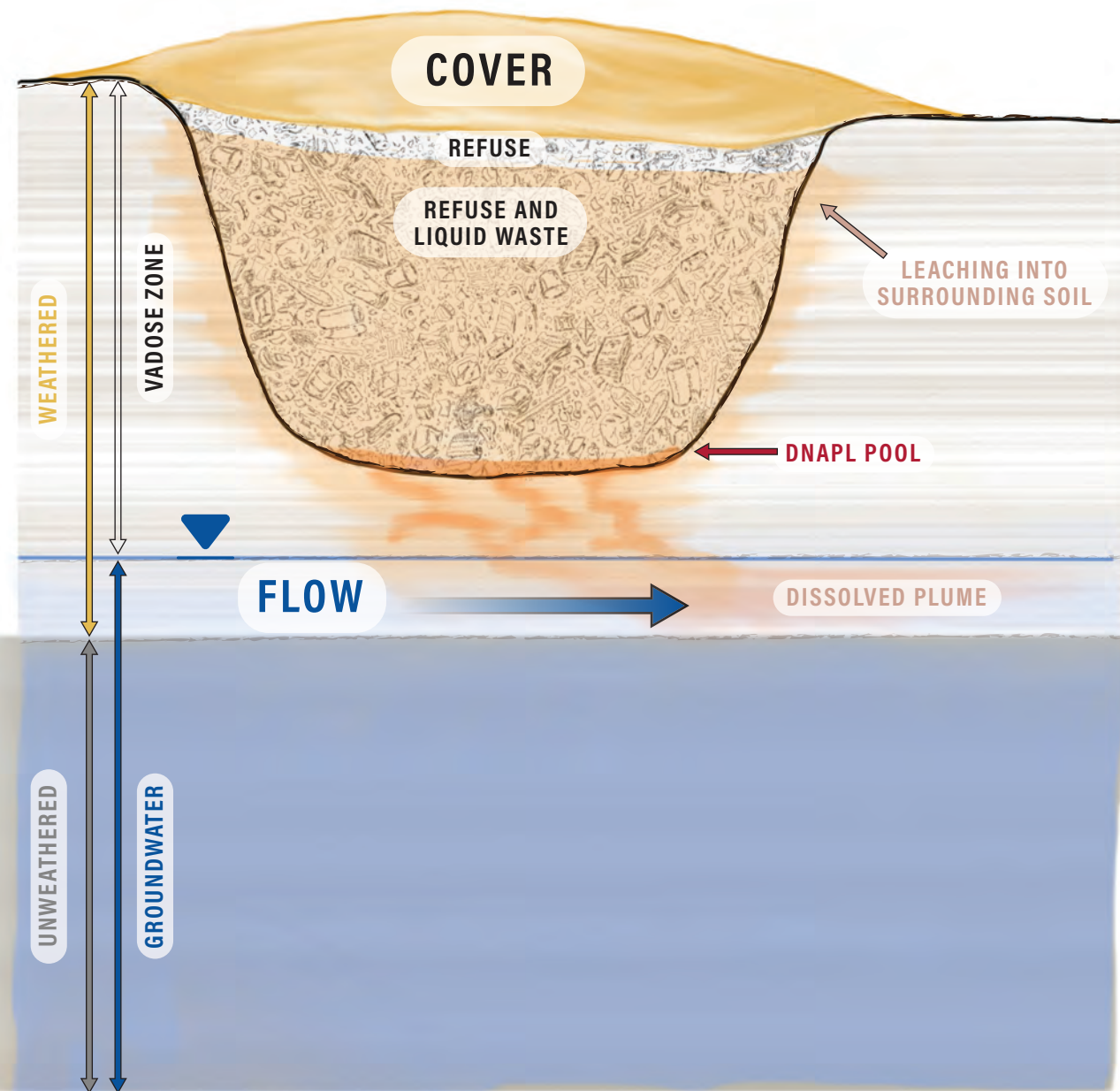
LOWRY LANDFILL SUPERFUND SITE

Arapahoe County, Colorado

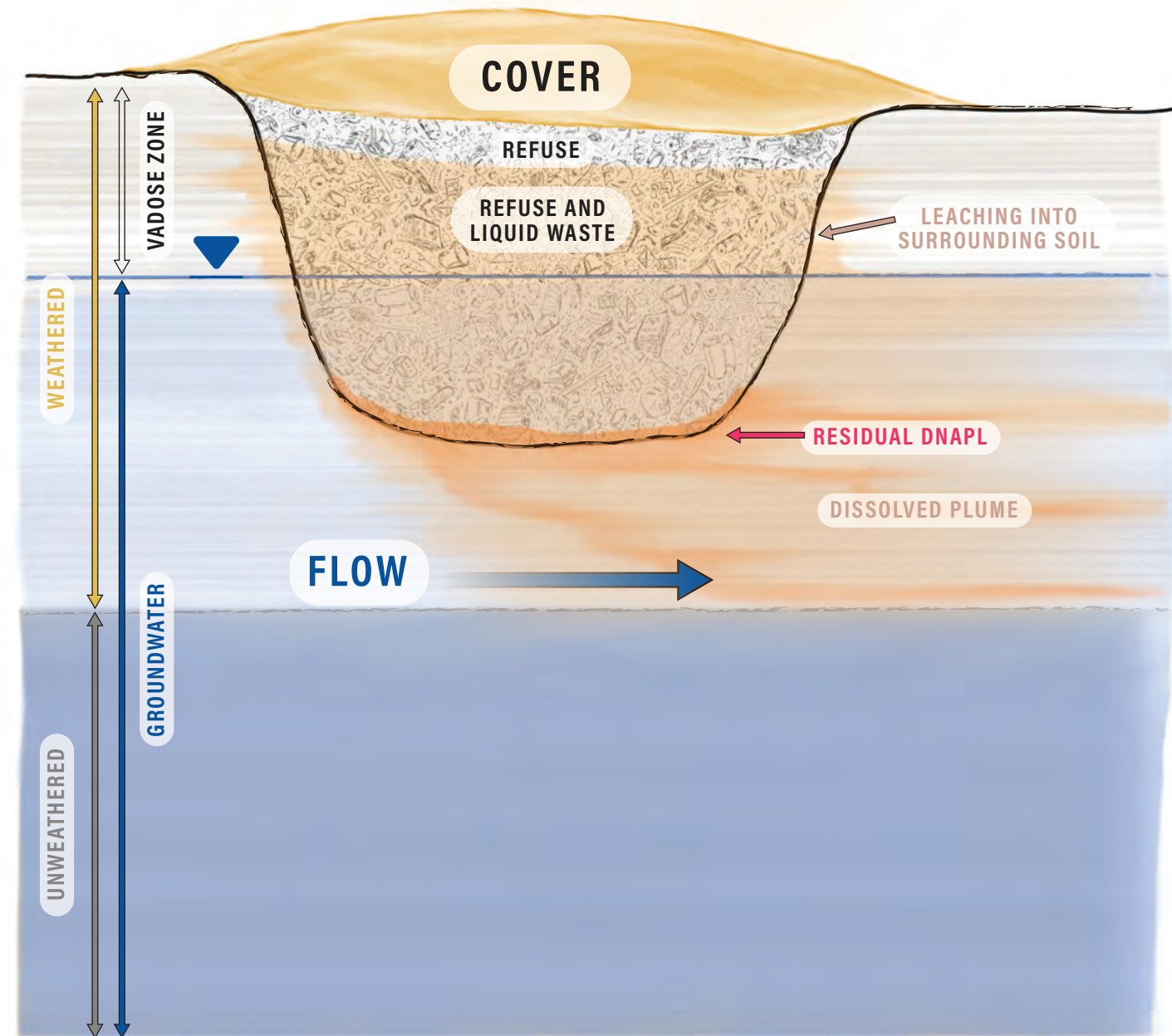
Figure 3-4  
Northern Extent of 1,4-Dioxane Plume



### 3-1 (a) Waste Pit / Trench *Above Water Table*



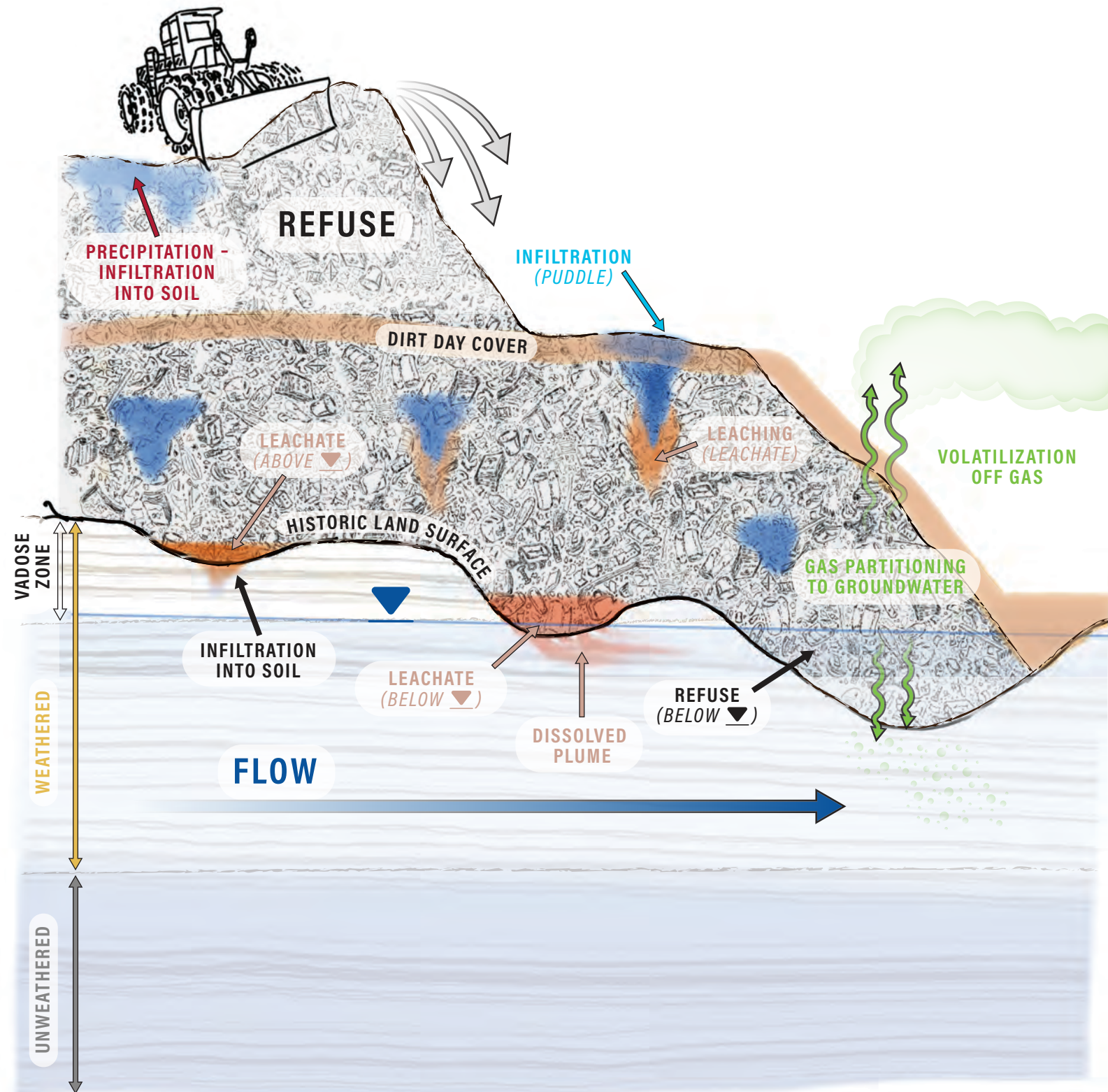
### 3-1 (b) Waste Pit / Trench *Intersecting Water Table*





# 3-2 Landfill Cross Section

## *Landfill Operation*



## 4.0 Geology and Hydrogeology

This section describes the geology and hydrogeology that underlies the site.

### 4.1 Geology

This section summarizes the regional and site-specific geology. The site-specific geology is described in detail in Sections 4.1 to 4.4 of the RI report for OUs 1 and 6 (HLA 1992).

Lowry Landfill is located within the Denver Basin, a north-south trending structural depression that extends north from Pueblo, Colorado into Wyoming. The basin is strongly asymmetric, with a gently dipping eastern flank bound by the Great Plains and a steep to overturned western flank bound by the Colorado Front Range. The basin consists of two widely separated structural lows, one centered near Denver, Colorado, and one centered near Cheyenne, Wyoming. Lowry Landfill is situated in the Denver structural low, near the center of the basin and immediately east of its axis (HLA 1992).

The Denver basin formed as a peripheral foreland basin during the uplift of the Front Range from the Late Cretaceous Epoch to the middle of the Eocene Epoch (Colorado Geological Survey [CGS] 2011). Deposition within the Denver basin consists of volcanically derived sedimentary material shed from the newly formed Front Range mountains. During active basin infill, sediment was being transported into the Denver Basin regionally from west to east and locally from southwest to northeast by surface water transport (Figure 4-1). During the Late Cretaceous Epoch (85 to 65 million years before present) sediments being transported off the uplifting Front Range were deposited to the east into the Cretaceous age Interior Seaway (CGS 2011). As time moved forward the Front Range continued to uplift and the Denver Basin filled in such that the character of sediments in the upper Denver and the overlying Dawson Formation shifted to represent Eocene and Paleocene age (65 to 35 million years before present) fluvial strata deposited by rivers draining the mountains to the west (CGS 2011).

The shallow-most geologic formations are the Dawson Formation (Dawson Arkose), including the upper (weathered<sup>7</sup>) and lower (unweathered) Dawson Formation, and the Denver Formation, as shown on Figure 4-2 and 4-3. North of the LLSS compliance boundary, the geology at the land surface transitions from the Dawson Formation to the Denver Formation and the Dawson Formation is no longer present. There are no features distinguishing this transition visible at ground surface that would allow this transition to be mapped.

The Dawson Formation is overlain by Quaternary age surficial deposits (alluvium), consisting of stream channel and floodplain materials, terrace deposits, and eolian sands. In some areas Quaternary age streams and rivers have eroded into the Dawson formation, depositing more modern stream channel sands within the older Dawson formation. The alluvium is often difficult to distinguish from the weathered portion of the Dawson formation near the ground surface as both facies are similar in appearance. The presence of alluvium at the site is thought to be limited to drainage channels (HLA 1992). The alluvium associated with the western tributary to unnamed creek was excavated during the surface water removal actions described in Section 5.0. Alluvial channels have been identified in the vicinity of MW38 Area and east of monitoring well MW-77 (EMSI 2007a).

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<sup>7</sup> Weathering is the process of breaking down rocks, soil, or minerals at or near the Earth's surface through physical, chemical, or biological processes resulting from contact with the atmosphere, water, and biological organisms.

The Dawson Formation (Dawson Arkose) unconformably overlies the Denver Formation and is the uppermost bedrock unit in the Denver Basin. The Denver and Dawson Formations are divided by a paleosol, or fossil soil, which is a soil horizon representing a prehistoric ground surface which was then buried under later sedimentation (CGS 2015). The paleosol at the bottom of the Dawson formation is a distinct zone of gray to pink to dark red clays up to 40 feet thick containing abundant plant root clasts, pollen, and poorly preserved plant fossil fragments. This paleosol also roughly represents the Paleocene-Eocene boundary (Raynolds 2002; Thorson and Madole 2002; and Thorson 2003) and previous geologic dating places this boundary at approximately 55 million years before present (CGS 2015). This regionally extensive low permeability paleosol corresponds to the Separation Layer described in detail by the CGS (2015) and historically in LLSS site documents (e.g., HLA 1992). The Separation Layer is the legally defined boundary between the Dawson and Denver Aquifers because this layer is regionally extensive and consistent (HLA 1992).

This interpretation of the Separation Layer as the defined transition between the Dawson and the Denver formations stratigraphically as well as the Dawson and the Denver Aquifers is a recent clarification published by CGS (2015). During the RI and historically (Van Slyke, et al. 1988; Robson and Romero 1981a and b) the Separation Layer was interpreted to be the transition between the Dawson and Denver Aquifers but the stratigraphic transition between the Dawson and Denver formations was previously defined as the first appearance of a significant lignite layer which occurs approximately 60 to 100 feet lower. This clarification in interpretation solves a long standing inconsistency in interpretation between the stratigraphic and hydraulic definitions of the transition between the Dawson and the Denver.

According to Romero (1976) and CGS (2015) the Dawson Formation includes all of the predominately quartzose and arkose sediments above the darker sandstones and shales of the Denver Formation, although the contact between the formations is not easily discernable in some areas where the paleosol facies are similar to Dawson or Denver Formation strata above and below. Soister (1978) finds the contact more definitive based on lithology and age. In general, the Dawson Formation consists of conglomerates and sandstones interbedded with lesser amounts of siltstones, shales, and local lignitic coal beds (Romero 1976 and Thorson 2011). At LLSS, the Dawson Formation thickness ranges from 180 to 310 feet, and the coarser portions of the formation are not present; rather, the formation is described as consisting of predominately claystone and siltstone with lesser amounts of interbedded sandstones.

The Dawson Formation strata are representative of a fluvial stream and river driven depositional environment. The Dawson and Denver Formations were primarily deposited in meandering<sup>8</sup> streams and associated floodplains. Three fluvial deposition cycles associated with the Dawson Formation at the site include (P.E. LaMoreaux and Associates, Inc. 1991):

- Channel fill deposits consisting of gravel or coarse- to very fine-grained sands;
- Overbank sands consisting of medium- to very fine-grained sands; and
- Siltstones, claystones, and occasional beds of lignite at greater depths.

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<sup>8</sup> Meanders are curves, bends, or windings in the channel of a waterway that are produced by a stream or river as it swings side to side across its floodplain or channel; sediment is eroded from the outer cut bank and then deposited downstream on an inner bank.

These fluvial depositional cycles are represented in Illustration 4-1 and in greater detail in Illustrations 4-2 (a) and (b). The sandstones and conglomerates of the Dawson Formation are channel and overbank deposits associated with fluvial deposition. Both channel and overbank deposits may occur as discontinuous lenses, although some channel sands are thought to be relatively continuous in directions paralleling ancient flow systems. There is thought to be a general fining upward sequence in the Dawson Formation, which is shown on the illustrations. In some areas, lag deposits<sup>9</sup> have been observed. Illustration 4-2(a) shows the processes of erosion, lateral deposition, and longitudinal channel sand deposition. Overbank and floodplain deposits are shown on Illustration 4-2(b).

Channel sands are relatively continuous in the direction of paralleling ancient flow systems, as shown on Illustrations 4-3(a), (b), and (c). Meandering streams are generally bound laterally by watershed or topographic highs or by terrace deposits on both sides of flood thalweg<sup>10</sup> (Illustrations 4-3[a] and [b]). Illustration 4-3(c) shows a longitudinal cross section of a flood thalweg with channel sands and floodplain deposits. The illustrations show vertical stacking of channel sands and the discontinuity of the sand lenses.

The uppermost portion of the Dawson Formation at the site is weathered bedrock, which ranges from 40 to 70 feet thick at the south end of the site, and from 20 to 30 feet in the vicinity of the NBBW. The weathered Dawson is characterized by poorly indurated, friable sandstones and weak to moderately indurated claystones and siltstones.

Depth of weathering in the Dawson Formation is identified on the basis of color (orange-brown), degree of hardness, mottling, and fracture density. The RI (HLA 1992) notes that the depth of weathering can be variable, and accurate delineation of the contact with the unweathered zone in individual borings was described as complicated due to the difficulty of distinguishing older from more recent oxidation zones. Lithologic data from soil borings at the site, including those resulting from recent investigations, were used to visualize the interface between the weathered and unweathered lithology, shown on Figure 4-4. This interface was identified by a geologist at the time the borehole was logged or by interpreting historical borehole logs based on the current understanding of the site lithology. The interface of the weathered/unweathered lithology for the North End area is shown on the cross-sections on Figures 4-5 and 4-6. The correlation of the many interface elevations from borings at the LLSS site establishes a weathered/unweathered surface elevation that is well defined. The portion of the weathered/unweathered interface between the Lowry Landfill and NBBW mimics surface topography, which suggests that there is consistency in the depositional environment from the ground surface to the unweathered lithology.

The Dawson Formation below the weathered/unweathered interface is described in LLSS boring logs as consolidated materials (rock) (i.e., claystone or sandstone), as shown on Figure 4-7. At LLSS, the base of the Dawson Formation and the top of the Denver Formation was identified in the RI as the top of the first thick lignite bed. However, based on the most recent interpretation from CGS, discussed above, the separation layer is actually the boundary between the two formations. According to the RI, the lignite that separates the Dawson (Arkose) Formation from the Denver Formation is regionally extensive and

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<sup>9</sup> A lag deposit is the deposition of material winnowed by physical action. Aeolian, fluvial, and tidal processes can remove the finer portion of a sedimentary deposit, leaving the coarser material behind.

<sup>10</sup> A thalweg is a line drawn on a map along the lowest points of a streambed or valley in its downward slope. The thalweg defines the deepest channel and thus, the natural flow direction of a waterway.

laterally continuous across the site and varies in thickness from 7 to 12 feet. Vertical transport of contaminants through the lignite later and into deeper groundwater below is not evident. Groundwater samples from monitoring wells indicate that deeper aquifers are generally not impacted by contamination (EMSI and Parsons 2020 and historical SSR documents). This lack of vertical migration is likely due to the low vertical hydraulic conductivity of sedimentary soils with respect to the lateral hydraulic conductivity of the same soils. This difference in vertical versus lateral soil permeability is called vertical anisotropy and is a known property of sedimentary rocks and soils (Todd 1980). Such vertical anisotropy results in preferential lateral movement of water and associated dissolved phase contaminants and inhibits vertical migration.

The Denver Formation underlying the site is characterized by interbedded sandstones, claystones, siltstones, fine-grained sandstones, and lignite beds. At the site, the Denver Formation consists dominantly of interbedded claystones and siltstones, with interbedded, thin to thick arkosic sandstones and minor conglomerates. The fluvial deposits of the Denver Formation, derived from andesitic and basaltic volcanic rocks, impart an overall darker olive to green-gray color to the formation. According to the RI report (HLA 1992) and more recently reports published by CGS (2011 and 2015), fining-upward sand sequences suggestive of fluvial channel deposits were identified on geophysical logs from at least two wells drilled at the site. Lignite as thick as 20 feet may be present within the Denver Formation. The upper lignite layer in the Denver Formation is described in detail in Soister (1974) as a relatively thick zone of thin lignite beds interspersed with claystone, siltstone, and kaolin beds. Based on geophysical logging performed at 18 locations at the time of the RI, the depth to the top of the Denver Formation is approximately 260 feet, and the depth to the base of the Denver Formation was approximately 1,004 feet (HLA 1992). Therefore, the formation thickness of the Denver Formation is approximately 744 feet.

Fractures<sup>11</sup>, in the form of cracks and joints, have been observed in the rock units at the LLSS; however, as stated in the RI report (HLA 1992) and supported by all subsequent investigations, no faults<sup>12</sup> have been identified at the site. Two normal faults with 2 to 3 feet of offset were observed in a stream cut near the Senac Dam (CH2MHill Inc. 1987). One interpretation hypothesized these to be growth faults<sup>13</sup> that formed contemporaneously with sediment deposition and did not extend to significant depths (HLA 1992). Extensive geophysical, drilling, and sampling work conducted at LLSS and surrounding vicinity does not support the presence of growth faults beneath LLSS (EPA 2013a). Even so, a growth fault involves displacement of soft sediments (e.g., slumping) that occurs during the time the sediments are deposited and does not result in enhanced fluid transport pathways associated with tectonically induced faulting. Fault patterns located north and south of the site, including the heavily studied Boulder-Weld Fault Zone, indicate faults are most likely northeast-striking. Gravity, magnetic, and seismic reflection data for the site suggest that a potential normal fault may underly the site, striking northeast and

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<sup>11</sup> Fractures are defined as any break in a rock resulting from mechanical failure by stress, regardless of whether it causes displacement of the rock on either side of the fracture. Fractures include cracks, joints, and faults.

<sup>12</sup> Faults are defined as a fracture or zone of fractures along which there has been displacement of the rocks on either side relative to one another.

<sup>13</sup> The term “growth fault” applies to instability that occurs when sediment is deposited over geologic time on top of a saturated evaporite layer, causing the pressure to build. The pressure is slowly released over time as the instability creates a fault zone where the hanging wall block slips down at a rate of 0.2 to 1.2 millimeters per year while active. Eventually the pressure re-equilibrates as sediment deposition rates change through time.



dipping southeast. The depth of the uppermost expression of the potential fault is at approximately 100 feet below ground surface (bgs) and is below impacted groundwater at the site, indicating it would have no apparent influence on contaminant migration from the site through groundwater (PWT and Tetra Tech 2017).

Fractures are forms of brittle deformation that generally occur in non-crystalline sediments such as those present in the Dawson and Denver formation. Fractures at the site are a result of the combined effects of consolidation followed by the release of overburden pressure resulting from erosional removal of the overlying sediment material. Fracturing at the site does not appear to be related to regional tectonism, based on the lack of patterned orientation (HLA 1992).

Fractures observed at the site generally occur as (1) open and iron-stained, (2) healed or filled, or (3) tight and slickensided. These fractures generally occur within 50 feet of the ground surface and within the average depth of weathering. The limited observations of open or iron-stained fractures were above depths of 50 feet. Most of the deeper fractures are described as tight or slickensided. Below the depth of weathering, fracture apertures close and groundwater movement diminishes (HLA 1992). Bedrock pumping during the RI indicated a best-estimated hydraulic conductivity of  $1 \times 10^{-8}$  centimeters per second for the Upper Denver Aquifer silts and clays (HLA 1992). This value is typical of unweathered clay (Bear 1972). Distribution of contaminants in groundwater discussed in Section 6.0 strongly suggests that fracture flow is not a significant component in the unweathered bedrock at the site. Site data indicate that depositional sands, especially in weathered material, provide preferential migration pathways and that topography, paleo-topographic surface, and paleo-depositional environment control present-day groundwater flow dynamics. This conceptual understanding of the impact of faults and fractures on this type of depositional environments supports the assumption that fault and fracture occurrence is not significant to groundwater flow and contaminant migration from the LLSS.

## 4.2 Hydrogeology

The primary water-bearing units at the site include the alluvium; permeable zones within the weathered bedrock (sand layers and channels, fractured zones, and other geologic discontinuities); the sandier portions of the unweathered Dawson Formation; and underlying formations extending to the Pierre Shale (EPA 2001b). Groundwater at the site exists in two major systems (shallow and deep), each with two aquifer zones, based on differences in hydraulic conductivity or regionally defined boundaries. The hydrostratigraphic units at the site are listed below from shallowest to deepest and are shown on Figure 4-8:

- Shallow groundwater (OU1)
  - Alluvium and weathered Dawson (0 to approximately 60 feet bgs)
  - Unweathered Dawson (approximately 30 to 120 feet bgs)
- Separation Layer (confining unit, not an aquifer)
- Deep groundwater (OU6)
  - Upper Denver Formation (approximately 120 to 210 feet bgs)
  - Lignite Layer (approximately 200 to 350 feet bgs)

As stated in Section 4.1, the geology at the land surface north of the LLSS compliance boundary transitions from the Dawson Formation to the Denver Formation. The definition for OU1 (shallow groundwater and subsurface liquids) beneath Section 6 refers to the weathered Dawson formation as

the shallow water bearing unit; however, shallow groundwater north of the site is in the Denver Formation because the Dawson Formation and the separation layer are absent in this area. The ROD evaluated OUs 1 and 6 collectively beneath LLSS, including the identification and evaluation of risk, applicable or relevant and appropriate requirements, RAOs, and remedial alternatives. Because the change in the formation at the surface north of LLSS does not fundamentally alter the sitewide remedy presented in the 1994 ROD (or subsequent amendments) or the evaluation of site risks or remedial alternatives, EPA determined the OU definitions do not need to be changed to reflect conditions north of the site.

Hydrogeologic conditions at the site are heterogeneous and anisotropic<sup>14</sup>. Groundwater flow within the shallow and deep systems is predominantly to the north, however, the shallow groundwater system also shows localized components of flow to the northeast and east. Subsurface conditions beneath the site consist predominantly of low permeability silt and clay deposits with lesser amounts of channel sands and associated fine-grained overbank deposits. Channel deposits within the Dawson Formation that have a relatively high degree of interconnection and resultant groundwater flux represent the primary and most significant potential pathways for groundwater migration. The location and extent of all sand channels may be unknown however significant investigation efforts have been conducted to date to map identified sand channels (e.g., MW38 sand channel) and implement remedial components to prevent the offsite migration of contaminants. It is reasonable and prudent to assume there may be unknown sand channels that are oriented such that they may permit offsite flow of contaminants (EPA 2001b). However, data collected during groundwater monitoring program sampling from the extensive network of site monitoring wells indicates that impacts to groundwater are well defined and site related contaminants present at concentrations in excess of Sitewide Groundwater Performance Standards beyond the property line are limited to 1,4-dioxane in the North End (EMSI and Parsons 2020, historical SSRs, and EMSI and CDM Smith 2020b). Nearly all the contaminant mass in groundwater is found in the alluvium and the weathered Dawson groundwater.

Although channel sands and overbank deposits are present within the Dawson Formation, flow into and out of the channel deposits and overbank sands is primarily controlled by the overall lower permeability matrix of the surrounding and encompassing claystones and siltstones of the Dawson Formation. The soil texture and particle size of more permeable sand versus less permeable silts and clays is shown on Illustration 4-4(a). Illustration 4-4(b) shows the reduction of pore spaces during the compaction of fine-grained silts and clays and the cementation<sup>15</sup> of coarse-grained sands.

Shallow groundwater at the site is defined as groundwater within the alluvium and weathered bedrock in the Upper Dawson Formation within the site boundaries. The weathered Dawson lithology is more similar to the overlying alluvial aquifer than the underlying unweathered lithology with respect to its ability to transmit groundwater (EPA 1994). In areas north of the site boundary, the Denver Formation is shallower, and the upper portions of the Denver Formation have been weathered (Figures 4-2 and 4-3).

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<sup>14</sup> Anisotropy is the property of being directionally dependent, as opposed to isotropy, which means homogeneity in all directions. Anisotropic soil does not have the same physical properties when the direction of measurement is changed (Encyclopedia of Agrophysics).

<sup>15</sup> Cementation occurs when ions in groundwater precipitate to form crystalline material between sedimentary grains.



Weathered bedrock is that portion of the formation, nearest to the ground surface, that has increased ability to transmit groundwater because of the natural weathering actions of physical and chemical processes. Physical weathering reduces particle size primarily by abrasion. Abrasion resulting from erosion transport of bedload is shown on Illustration 4-2(a). Physical reduction of particle size increases the particle surface area, which can increase the effect of chemical weathering. Chemical weathering involves the direct effect of atmospheric chemicals or biologically produced chemicals in the breakdown of rocks, soils and minerals. Chemical weathering processes include dissolution and carbonation, hydration, oxidation, and biological weathering. All of these processes are believed to be active at the LLSS.

Weathering can increase groundwater flow by removing cement present between mineral grains. Illustration 4-5 depicts the presence of calcite cement in weathered and unweathered lithology. As the cement is dissolved by chemical weathering, oxygenated groundwater flow between mineral grains can increase, as shown on Illustration 4-6. Chemical weathering propagation<sup>16</sup> is generally controlled by time and exposure to the atmosphere, lithology, and oxygenated groundwater. An example of weathering along a flowing stream is shown on Illustration 4-7. As shown on the illustration and observed in soil cores at the LLSS, the weathered/unweathered surface generally mirrors topography but can deepen in saturated channel sands. The illustration also shows the weathered/unweathered surface deepens where two channel sands are in communication with each other, and the groundwater flow is enough to weather the sands within the ancient channel.

In November 2019, molybdenum was detected in effluent from the WTP at concentrations higher than the discharge limits allowed by Metro. The WSDs took immediate actions to modify the extraction rate at well MW113-EW-1 to meet WTP discharge limits and to identify the source of the high molybdenum concentrations (EMSI and CDM Smith 2020c). The maximum concentration of molybdenum detected at the site was 42,000 micrograms per liter ( $\mu\text{g/L}$ ) at MW113-WD on June 4, 2020. The extent of molybdenum that exceeds the Colorado Basic Standard for Groundwater (CBSG, 210  $\mu\text{g/L}$ ) in shallow groundwater in the NBBW area is shown on Figure 4-9. The molybdenum concentrations exceeding the CBSG appears to be coincident with a localized groundwater table depression caused by cessation of potable water injection and groundwater extraction and limited to a deep truncated paleochannel scour filled with relatively high-energy channel sands. The scour feature had an elongated bowl-shaped configuration, defined by the weathered/unweathered interface. X-ray fluorescence testing and laboratory analysis of soil core from the area indicate that elevated molybdenum in soil is highly localized and present in high-energy sands and clay clasts at the base of the weathered bedrock hydrostratigraphic unit. Clay clasts or molybdenite flakes with elevated molybdenum concentrations may have eroded from upgradient sources and transported as bedload<sup>17</sup> to the site.

The sediments that make up the Dawson and Denver Formations are volcanic in origin and are chemically and texturally immature (Paschke et al. 2014). As a result, Dawson and Denver Formation strata naturally contain elevated concentrations of metals species (e.g., molybdenum, selenium, iron, lead, etc.). Fine grained, organic rich strata like coals and lignites are particularly rich in metals species because the organic materials tend to sorb soluble metal species during and after deposition (Paschke et

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<sup>16</sup> Chemical weathering is the erosion or disintegration of rocks by chemical reactions, often transforming them when water interacts with minerals (hydrolysis). Chemical weathering is a gradual and ongoing process.

<sup>17</sup> Bedload is sediment that is rolled or dragged along a stream bottom.

al. 2014). During the subsequent erosion and natural chemical weathering of these strata the solid phase metal based minerals (e.g., pyrite, galena, selenide) dissolve, liberating soluble metals and accompanying anions (e.g., sulfate, carbonate) to groundwater flowing through the strata. These processes have resulted in elevated concentrations of metals in groundwater in the vicinity of LLSS (Paschke et al. 2014; DeSimone et al. 2009; Herring and Walton-Day 2007).

At the LLSS, the lower unweathered Dawson aquifer is separated from the Upper Denver by the Separation Layer which is laterally extensive beneath LLSS and to the south, southwest, and southeast but has been eroded away north of LLSS. Where present, the Separation Layer consists predominantly of low permeability sediments. The depth of substantial lignite beds, approximately 350 – 380 feet bgs beneath LLSS (HLA 1992), referred to in the ROD as the Lignite Layer, is the deepest hydrostratigraphic unit monitored at the site and is the vertical point of groundwater compliance for the LLSS.

The weathered, unweathered, and lignite hydrogeologic units are described in more detail below.

#### Weathered Dawson

The saturated thickness of the weathered Dawson ranges from 0 (not present) to approximately 27 feet at the LLSS. In some portions of the site, the weathered Dawson is completely dewatered, and the unweathered/weathered interface is above the water table, as shown on Figure 4-10.

Regionally, Dawson Aquifer groundwater is characterized as a calcium bicarbonate type, with sodium bicarbonate or sodium sulfate water types occurring in a few isolated areas (Robson 1987). Localized deposits of gypsum and related evaporite minerals occur east of the Cherry Creek Reservoir (north of Section 6) near the poorly defined contact between the Denver and the Dawson Formations (Robson and Romero 1981a, 1981b). When groundwater in the Dawson Formation comes into contact with these soluble sulfate minerals, the groundwater changes from calcium bicarbonate to a sodium sulfate type, and the dissolved solids concentration of the water increases significantly (Robson and Romero 1981b). Groundwater collected during the RI and the North End Investigation was typed using a Piper diagram<sup>18</sup> as calcium sulfate water. Water types in the Dawson and Denver formations are shown on Illustration 4-8. In the vicinity of the LLSS, the concentration of dissolved solids in the Dawson Aquifer ranges from 1000 to 1500 milligrams per liter (mg/L) (Robson and Romero 1981b). Dissolved sulfate is greater than 250 mg/L, and the water is very hard (greater than 180 mg/L as calcium carbonate) (Robson and Romero 1981b).

Site-specific hydraulic conductivity measurements were derived from in-situ slug and packer tests performed for the RI, which were correlated according to lithologic classification of the dominant lithology (HLA 1992). Geometric mean values reported on RI Table 4.13 were 1.7 feet per day for sandstones (weathered sands) and 0.03 feet per day for claystones (weathered clays) in the weathered Dawson. The reported range of hydraulic conductivity (Kh) for weathered sandstones in the weathered Dawson based on nine slug and packer tests varied from 0.001 to 2,300 feet per day, a variation of more than five orders of magnitude.

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<sup>18</sup> A Piper diagram is a graphical representation of the chemistry of a water sample in the form of a trilinear diagram showing cations and anions. Piper diagrams are used to compare multiple samples or show trends in major ions.

The hydraulic conductivity of weathered and unweathered material was also calculated as part of the North End Investigation (EMSI and CDM Smith 2020b). Rising head and falling head slug tests were completed to evaluate the permeability of the water bearing zones in the North End study area. In general, the geometric mean values of lateral hydraulic conductivity for both weathered and unweathered lithologies compared well with those in the RI. The geometric mean hydraulic conductivity in the weathered material was 7.64 feet per day for sands and 0.288 feet per day for clays/silts. Comparison of lateral hydraulic conductivity values between North End wells and LLSS wells demonstrate that the hydraulic properties of the source material (weathered and unweathered sands, silts, and clays) are similar (EMSI and CDM Smith 2020b).

The RI report (HLA 1992) assumed the total (bulk) porosity to be approximately 40 percent. Effective porosity for the weathered Dawson is listed as 0.28 percent in the RI and the kinematic porosity (the percentage of interconnected pore space that contributes to steady-state flux) is estimated to be 0.1.

Lithology information from site soil borehole logs was analyzed and visualized as relative hydraulic conductivity (or hydrolithology<sup>19</sup>) as part of the 3DVA (PWT and Tetra Tech 2020). Relative hydraulic conductivity is not a direct measure of actual hydraulic conductivity, which would be derived from well testing. Rather, it is an indexing of hydraulic conductivity based on lithologic information. As such, it provides a more uniform analysis of sitewide relative hydraulic conductivity to indicate potential groundwater flow and contaminant migration pathways than can be inferred from manual review of individual conductivity testing results from monitoring wells and soil borehole log information. The relative hydraulic conductivity was based on the Unified Soil Classification System (USCS) grain size classifications in the borehole logs. The USCS classifications were assigned a number that is based on the progressive changes in grain sizes in materials from fill to gravels through clay; for example, the number 1 was assigned to highly permeable gravel and the number 13 was assigned to low permeability silt and clay. The hydrolithology of the weathered geology is shown on Figure 4-11.

The hydrolithology in the weathered formations beneath the site is highly heterogeneous. The highest relative hydraulic conductivity areas are isolated on Figure 4-12; these areas indicate deposits (such as sands and gravels) that are comparatively more conducive to migration of the dissolved-phase contamination than silts and clays. High relative hydraulic conductivity deposits appear to be oriented north-south along the unnamed creek drainage between the NTES and the NBBW. This deposit appears to continue north of the NBBW, along the historical drainage of Murphy Creek. Another area of high relative hydraulic conductivity is located in the area known as the MW38 sand channel. Conversely, Figure 4-13 shows the deposits with the lowest relative hydraulic conductivity; these deposits (such as silts and clays) impede flow and transport of the groundwater contaminants.

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<sup>19</sup> Hydrolithology is an index-based approach to kriging geologic data, specifically, the distribution of relative hydraulic conductivities within different lithologies (soil types) at a site (that is, gravel, sand, silt and clay and all grain size variations between). Material descriptions in soil boring logs are classified based on the Unified Soil Classification System. The classifications are assigned corresponding numbers, based on progressive changes in grain size.

Cycles of flooding, sediment transport, erosion, deposition, and stream avulsions<sup>20</sup> have created horizontal and vertical channel sand discontinuities observed on Figure 4-12. These processes are shown on Illustration 4-9 and in more detail on Illustrations 4-9(a) through 4-9(d). Bank erosion and subsequent deposition is shown on Illustration 4-9(a). Illustration 4-9(b) shows how abandoned channels fill during high velocity flow and high sediment load events. The channel is filled with coarse-grained sediments, which results in an elongated sandy trough. This illustration also shows the formation of an oxbow deposit, or a channel fill consisting of fine-grained sediments. A clay plug develops in the available channel. A crevasse splay<sup>21</sup> deposit is shown on Illustration 4-9(c). A discontinuity is created between the splay deposit and a floodplain deposit. Chute, tributary, and eolian deposits that also create channel sand discontinuities are shown on Illustration 4-9(d). An avulsion in Murphy Creek approximately 0.75 mile south of Mississippi Avenue is shown on a 1965 aerial photograph (Illustration 4-10).

The lateral hydraulic gradient within the weathered Dawson near the site is influenced by the surface topography, discharge and recharge areas, and the groundwater remedy components. The potentiometric surface of the water table indicates the groundwater flow direction is generally to the north and converges along the drainage of the unnamed creek between the NTES and NBBW. Figure 4-14 shows the potentiometric surface and resulting isocontours and directional lines<sup>22</sup> based on data collected in 2018. Groundwater flow north of the NBBW generally follows the surface expression of the historical Murphy Creek drainage (Figure 4-15). Flow within the weathered Dawson at the site is also controlled by discharge and recharge areas, which are strongly influenced by topography, and evapotranspiration, which is cited as a major component of groundwater losses within the Denver Basin (Paschke 2011). Both the direction and the magnitude of the lateral gradient may deviate locally near drainages and ridgelines due to the movement of groundwater away from topographic ridges; convergent flow toward drainages; variations in stratigraphy such as depositional sand channels; or the hydraulic influence of groundwater extraction systems and other remedial actions. The groundwater remedies influence groundwater flow in the weathered Dawson, including the SWRA, groundwater extraction from collection drains and extraction wells, water injection (when injection was occurring), and the perimeter slurry wall systems. These features are described in Section 5.0. Groundwater flow in the MW38 channel converges within the channel and terminates at the extraction wells south of the DADS Landfill. Paired monitoring wells inside and outside of the perimeter slurry wall indicate the groundwater gradient is mostly inward toward the landfill mass, although in some areas, the groundwater gradient indicates the potential for outward flow through the slurry wall, such as near monitoring well pairs PM-13I/PM-13X or PM-14I/PM-14X (Figure 4-14).

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<sup>20</sup> Avulsion is the natural process by which flow diverts from an established river channel and forms a new river channel on the adjacent floodplain. Avulsions occur when the current channel slope is much less steep than the slope that the river could travel if it took a new course.

<sup>21</sup> A crevasse splay is a sedimentary fluvial deposit that forms when a stream breaks its natural or artificial levees. As the water flows out of its channel and spreads onto the floodplain, sediments will start to fall out of suspension and deposit on the floodplain.

<sup>22</sup> The directional lines were drawn perpendicular to the isocontours to represent potential groundwater flow pathways at the potentiometric surface. The lines do not consider anisotropy and changes in the hydrogeology of the subsurface. Therefore, the directional lines are not evidence of actual groundwater flow but illustrate the most likely path based on water elevation information.

The RI indicated a variation of the magnitude of the lateral hydraulic gradient in the site area from 0.01 to 0.06 feet/feet, but across the entire site, a value of 0.03 feet/feet is given. The lateral gradient measured during the first half of 2017 from PM-8I inside the slurry wall on the southern part of the site to well A-115 south of, but near the NBBW, was approximately 0.022 feet/feet (EMSI and Parsons 2017), which is similar to the range reported in the RI. The hydraulic gradient at the LLSS site ranged from approximately 0.015 to 0.026 feet/feet in January 2017 in the weathered Dawson. The lateral gradient was also measured in the North End area as part of the North End Investigation (EMSI and CDM Smith 2020b). Generally, the lateral hydraulic gradient within the alluvium/weathered lithology is approximately 0.008 feet/feet directed to the north-northwest.

Anisotropic conditions exist at the LLSS; these conditions are represented in clay and sandy soils on Illustration 4-11. Anisotropy is the property of being directionally dependent, as opposed to isotropy, which means homogeneity in all directions. The anisotropy ratio of horizontal to vertical hydraulic conductivity reported in the RI was 20:1 within the weathered Dawson (HLA 1992). However, as described earlier in this section, the hydraulic conductivity values span a large range (five orders of magnitude or more) by lithology. Furthermore, the anisotropy ratio is expected to be greater than that of individual materials because the effective vertical hydraulic conductivity is controlled by properties of claystone/siltstone and the effective horizontal hydraulic conductivity is controlled by the combined properties of claystone/siltstone and sandstone. Therefore, the RI report concluded that the anisotropy ratio of 20:1 is likely a low value and the large-scale anisotropy ratio may be as high as 100:1 for the weathered Dawson. Vertical impediments to downward flow are shown on Illustration 4-11. Because sand lithology units are generally discontinuous and positioned between siltstone and claystone units which have relatively low hydraulic conductivity values, vertical groundwater movement is constrained. The high reported anisotropy ratios result in strong preferential lateral groundwater flow and inhibition of vertical flow which reduces the potential for downward groundwater flow and contaminant migration.

There is little available data to determine what the vertical hydraulic gradient within the weathered Dawson might be. The RI reported a wide range of vertical conductivity values, from 0.000006 to 9 feet per day (HLA 1992, Table 4.13). A recent analysis of vertical gradients between the weathered and unweathered Dawson zones is presented in the First Half 2017 Status Report (EMSI and Parsons 2017) based on water level data that is typically collected several times per year. The analysis identified mostly downward gradients; however, areas of upward potential occur mostly around the NBBW groundwater extraction trench, where the weathered Dawson potentiometric surface has been lowered by groundwater extraction.

The North End Investigation calculated vertical hydraulic potential gradients between the weathered and unweathered units by dividing the head difference between the midpoints of the saturated well screens associated with weathered and unweathered well pairs. In the North End area, downward vertical potential gradients were observed in all well pairs, whereas upward vertical potential gradients were observed in the two well pairs located in Section 31. Downward vertical potential gradients ranged between -0.013 to -0.438 feet/feet. Upward vertical potential gradients ranged between 0.007 and 0.053 feet/feet (EMSI and CDM Smith 2020b).

Although downward and upward gradients were calculated in the RI and in more recent reports, these are only indicative of the potential gradient, assuming that the groundwater in two different monitoring

wells is completely connected, and do not indicate actual movement of groundwater or contaminants. Vertical flow is affected by the type, thickness, bedding configuration, and degree of fracturing of the material comprising, or separating the two hydrogeologic units. Connectivity between shallow and deep groundwater systems would require the geology to be relatively homogeneous, isotropic, and not be separated by layers or beds of low-permeable material such as fine soils (clays or silts), claystones, or siltstones. The site geology is heterogeneous and anisotropic and the shallow and deep groundwater systems are separated by low-permeability claystones and siltstones (Illustration 4-11). Therefore, the actual potential for downward migration of groundwater between units is likely insignificant to nonexistent at the site.

The potential connection between the shallow and deep groundwater units north of the LLSS was investigated as part of the North End Investigation in 2019 (EMSI and CDM Smith 2020b). The report concluded that there was no significant connection between the groundwater units in the North End study area based on (1) the presence of low-permeability sediments at or beneath the weathered/unweathered bedrock contact; (2) the lack of 1,4-dioxane detected in deep unweathered bedrock groundwater, (3) differences in nitrate concentrations detected in shallow monitoring wells (higher concentrations) and deep monitoring wells (lower concentrations), and (4) differences in water quality type in shallow groundwater (predominantly calcium sulfate), deep groundwater (sodium chloride), and deeper water supply wells (sodium bicarbonate).

#### Unweathered Zones

The sandstones, siltstones, and claystones of the upper Denver are not distinguished from the sandstones, siltstones, and claystones of the unweathered Dawson aquifer unit in the boring log data. Therefore, the unweathered Dawson and the upper Denver hydrostratigraphy are discussed together in this section. The thickness of the unweathered Dawson hydrostratigraphic unit, from the base of the weathered Dawson to the separation layer, is approximately 100 feet in the southern portion of the LLSS. The unweathered Dawson ranges from 60 to 80 feet thick near the toe of the landfill, and from 30 to 40 feet thick at the northern end of the site boundary. The Denver aquifer, or upper Denver varies in thickness from approximately 135 feet to approximately 150 feet at LLSS. According to the RI report, the upper Denver is dominated by claystones and siltstones that vary in thickness from 30 to 80 feet in the northern portion of the site, underlain by channel sandstones that range in thickness from 15 to 30 feet. The deposition of the claystone and sandstone units of the unweathered bedrock is shown on Figure 4-7. The visualization was based on macro-scale interpretations of the borehole logs (unweathered bedrock was characterized as claystone, sandstone, or lignite).

Most of the unweathered zone is fully saturated. The unweathered zone is not hydrologically isolated from the overlying weathered formations (that is, there is no continuous aquiclude or confining unit overlying the unweathered formation). However, groundwater transport from the weathered units to the unweathered units is likely insignificant as evidenced by the difficulty of extracting water from wells screened in unweathered zones and the shift in geology to consolidated materials and rock having lower permeability. The hydraulic conductivity of the unweathered bedrock units is approximately two orders of magnitude lower than that of the weathered Dawson, as indicated by slug and packer testing data documented in the RI report (HLA 1992). For the unweathered Dawson, the geometric mean lateral hydraulic conductivity in the RI was listed as 0.001 foot/day. Like the weathered Dawson, the reported range of hydraulic conductivity values in the unweathered Dawson also varies by approximately five orders of magnitude, from 0.000003 to 0.28 foot per day. Geometric mean values for unweathered

sands (0.03 foot per day) and unweathered clays (0.0006 foot per day) indicate that sandstones are likely to be about two orders of magnitude more permeable than the siltstones and claystones in the unweathered Dawson. The lateral hydraulic conductivity was also calculated as part of the North End Investigation (EMSI and CDM Smith 2020b). The geometric mean hydraulic conductivity in the unweathered Dawson was 0.0143 foot per day for sands and 0.00787 foot per day for clays/silts.

Effective porosity for the unweathered Dawson is listed as 0.27 in the RI and the kinematic porosity (the percentage of interconnected pore space that contributes to steady-state flux) was estimated to be 0.05 for the unweathered Dawson and upper Denver. Specific yield estimates for the Dawson Aquifer and Denver Aquifer found in the RI were 20 percent and 17 percent, respectively. Specific yield is a parameter necessary for evaluating transient effects of pumping. The specific storage for the unweathered Dawson and all lower units is assumed equal to  $2 \times 10^{-5}$  feet<sup>-1</sup>, equal to the results of a pumping test for upper Denver claystone cited in the RI report.

Regionally, the water of the Denver Aquifer is classified as a sodium bicarbonate type (HLA 1992). As described by Robson and Romero (1981a), total dissolved solids of the aquifer in the vicinity of the site are expected to be approximately 225 mg/L and hardness (as calcium carbonate) is approximately 60 mg/L.

The general regional flow direction in the unweathered zone is north-northeasterly. Local flow north of the site generally follows the Murphy Creek drainage and flows north-northwesterly (Figure 4-16). The potentiometric surface for the unweathered zones north of LLSS is shown on Figure 4-16. The horizontal gradient within the unweathered zone is roughly 0.01 to 0.04 foot/foot, depending on location, based on the piezometric contours included in the First Half 2017 Status Report (EMSI and Parsons 2017). In the North End area, the lateral hydraulic gradient within the unweathered lithology is approximately 0.012 feet/feet, directed to the north-northwest in Section 19 (EMSI and CDM Smith 2020b).

Anisotropy ratios of horizontal to vertical conductivity reported in the RI were 20:1 within the unweathered Dawson and upper Denver. However, as described earlier, the RI report concluded that the anisotropy ratio is likely a low value and that the anisotropy value may be as high as 100:1 for the unweathered Dawson and upper Denver. According to the RI (HLA 1992), vertical gradients within the unweathered Dawson, the separation layer, and the upper Denver are greatest in the southern portion of the site where there is greater difference in potentiometric levels between the systems and lessen to the north of the site.

Between the Dawson Arkose and the Denver Formation below, a separation layer has been previously characterized on the basis of gamma log signatures that are regionally correlatable. The separation layer is inferred to be dominated by clay shales that are 20 to 40 feet thick. The base of the separation layer is used to define the boundary between the shallow groundwater OU (OU1) and the deep groundwater OU (OU6) at LLSS (Illustration 4-12).

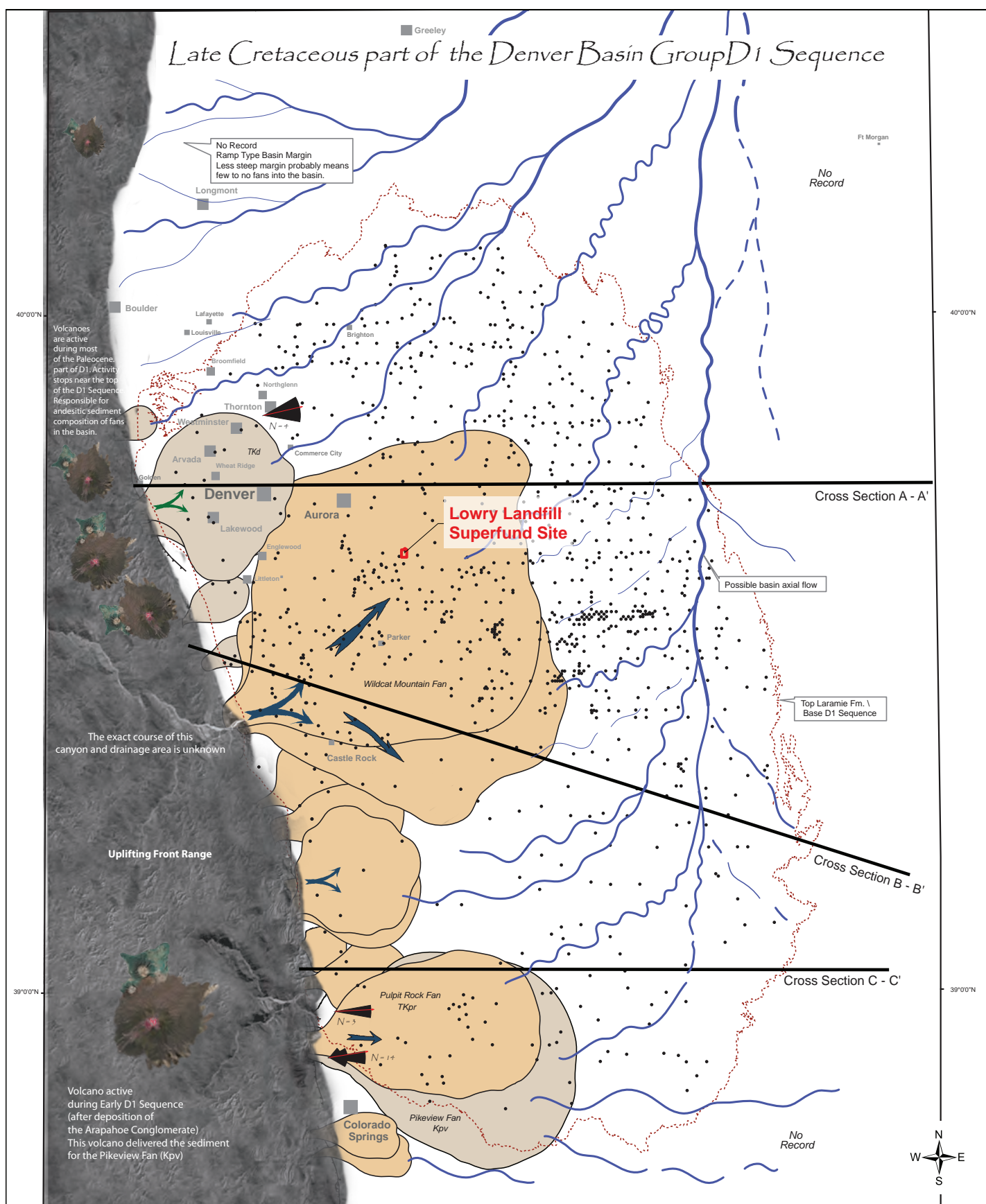
### Lignite

The depth of initial increased appearance of lignite beds, referred to as the Lignite Layer in the ROD, is the deepest hydrostratigraphic unit monitored at the site and is the vertical point of groundwater compliance for the LLSS (Illustration 4-12). The Lignite Layer is encountered beneath the upper Denver and indicates the boundary between the upper and lower Denver hydrostratigraphic units. This laterally and vertically extensive lignite layer is present approximately 350 to 380 feet bgs at LLSS. As described

in Section 4.1, the RI concluded that the Lignite Layer was laterally continuous beneath the site. This conclusion matches CGS interpretations of the Lignite Layer regionally and locally (Figure 4-7).

The RI indicated that flow within the lignite is to the north with a relatively uniform lateral gradient of approximately 0.004 feet/feet. The Lignite Layer possesses a higher hydraulic conductivity relative to the adjacent strata (upper Denver). Flow is expected to be primarily lateral within the lignite. According to the RI, the hydraulic conductivity of the lignite is relatively high ( $3 \times 10^{-6}$  centimeters per second, or  $8.5 \times 10^{-3}$  feet/day, as cited from pump test results) compared to the adjacent strata. The lignite is assumed to be isotropic; therefore, anisotropy ratios of horizontal to vertical conductivity reported in the RI were 1:1 for the Lignite Layer.





- Cities
- Wells used for analysis
- Denver Basin Cross Sections

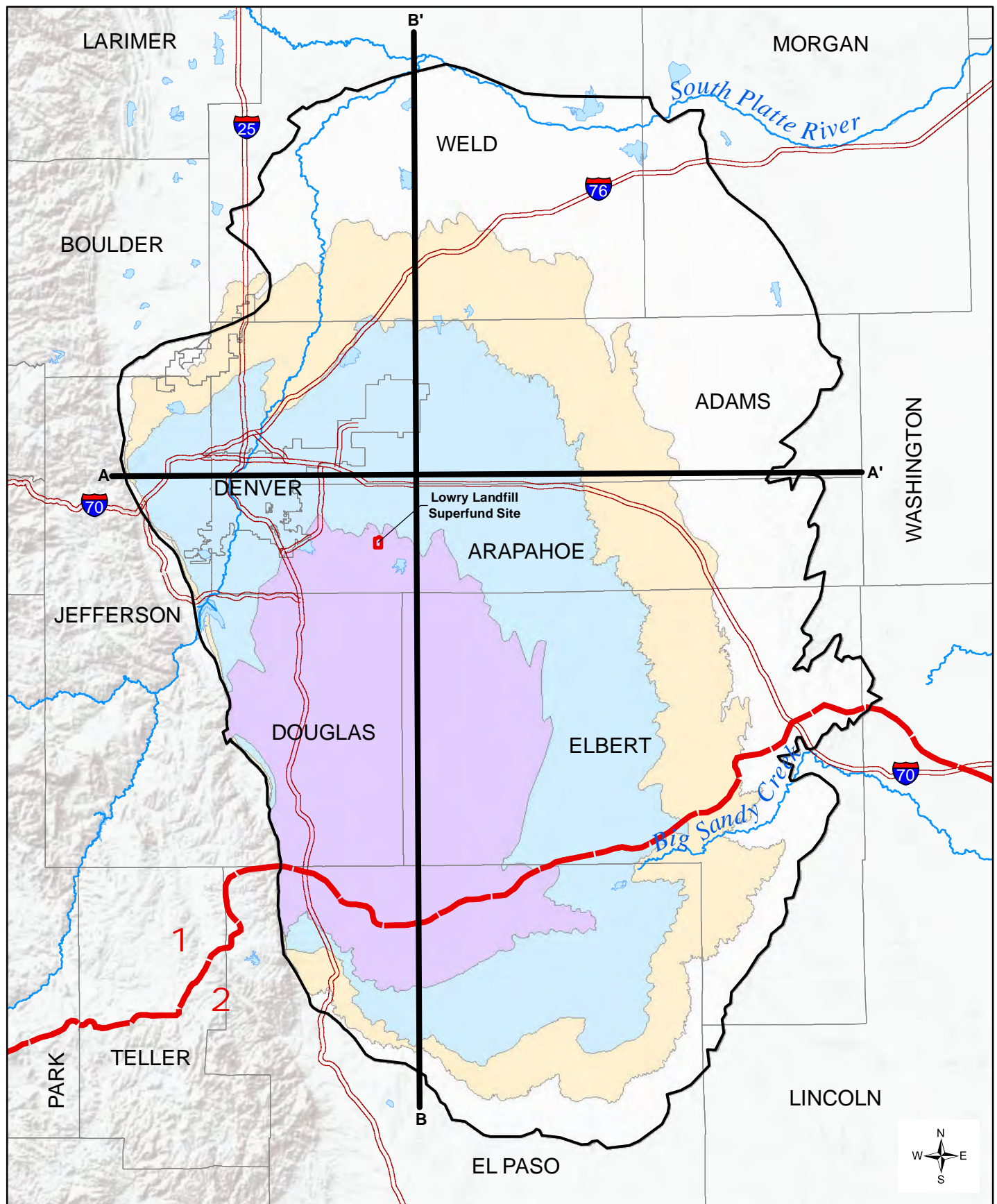
--- Outcrop Trace, showing the limit of surface and subsurface control

### LOWRY LANDFILL SUPERFUND SITE Arapahoe County, Colorado

**Figure 4-1**  
**Sediment Transport and Depositional**  
**Patterns during the Cretaceous Epoch**

Cross Sections Referenced on This Figure can be Found in CGS, 2013.  
Service Layer Credits: Sources: Colorado Geological Survey 2013

Source: Denver Museum  
of Nature & Science



- 1 Lowry Landfill Boundary
- 1 Water Division Boundary
- Dawson Basin

- Denver Basin
- Arapahoe Basin
- Laramie-Fox Hills Basin

Source: Figure 2-6 (ROD);  
CWCB; DWR; CDSS; USGS

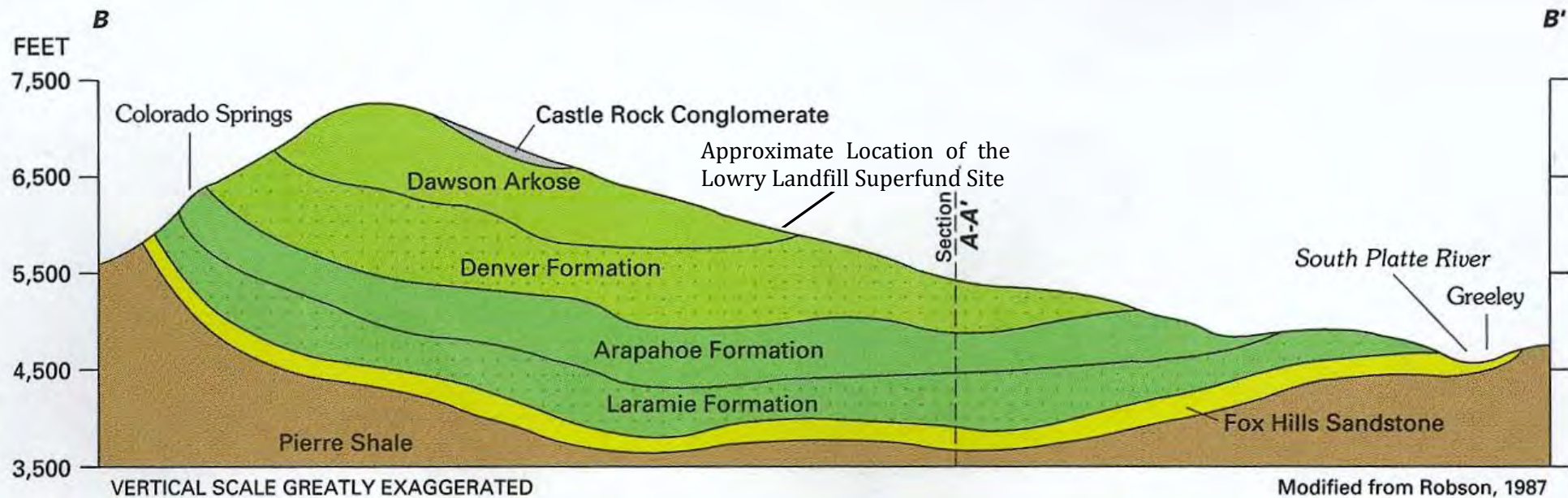
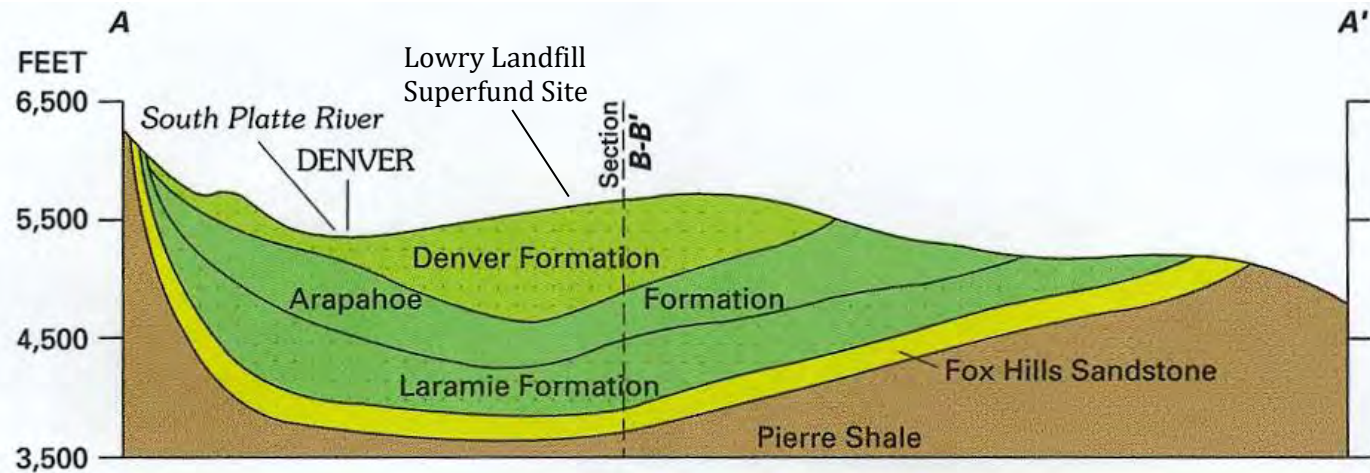
Service Layer Credits: Sources: Esri, USGS, NOAA

### LOWRY LANDFILL SUPERFUND SITE

Arapahoe County, Colorado

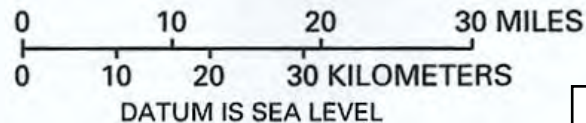
**Figure 4-2**  
**Cross-Section through**  
**the Denver Basin Aquifers**





VERTICAL SCALE GREATLY EXAGGERATED

Modified from Robson, 1987

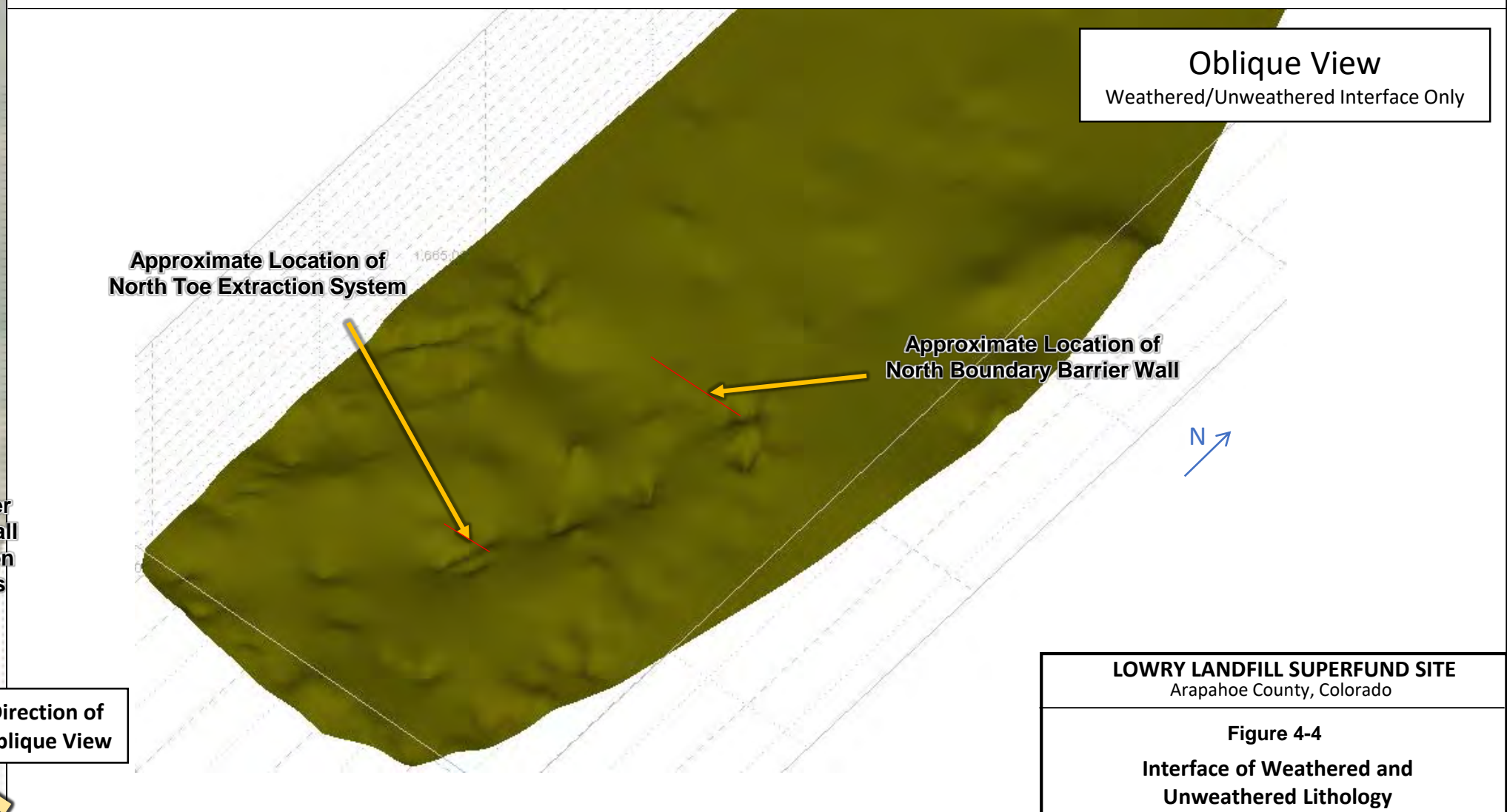
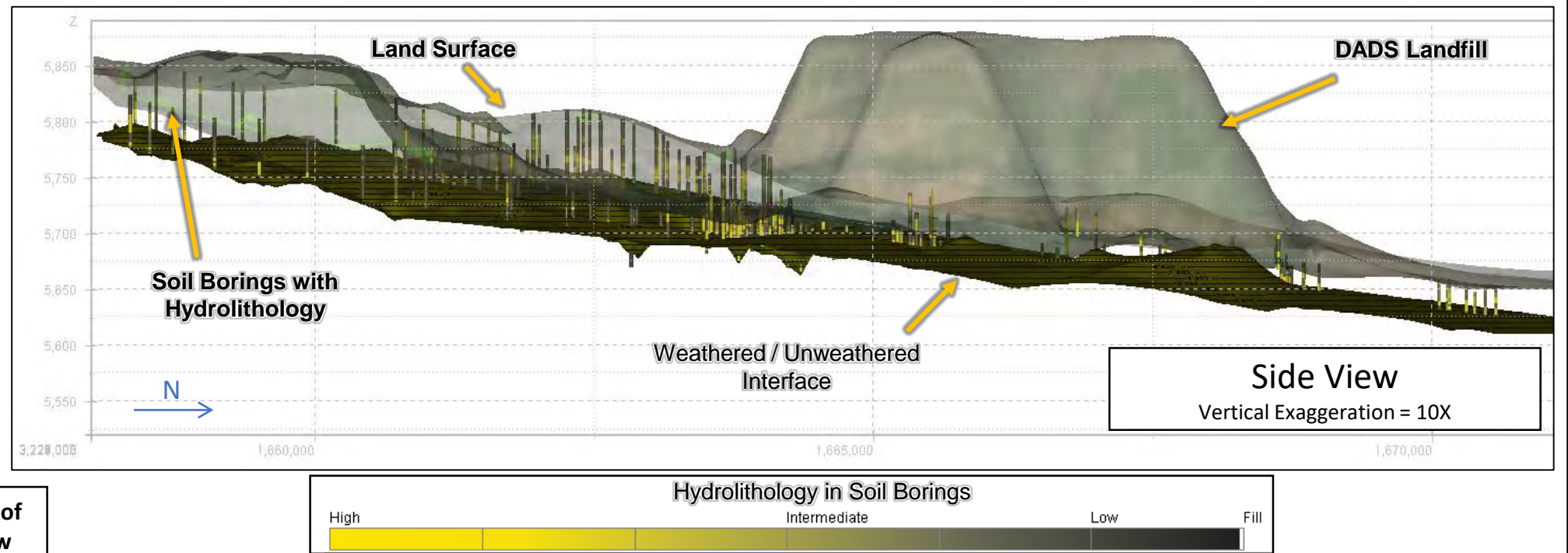


#### LOWRY LANDFILL SUPERFUND SITE

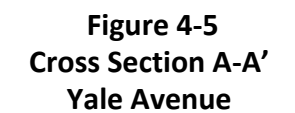
Arapahoe County, Colorado

**Figure 4-3**  
Cross Section through  
Denver Basin Formation



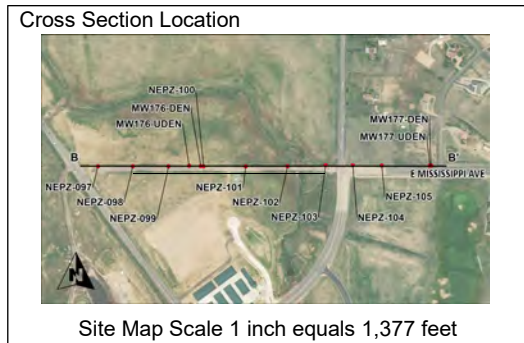
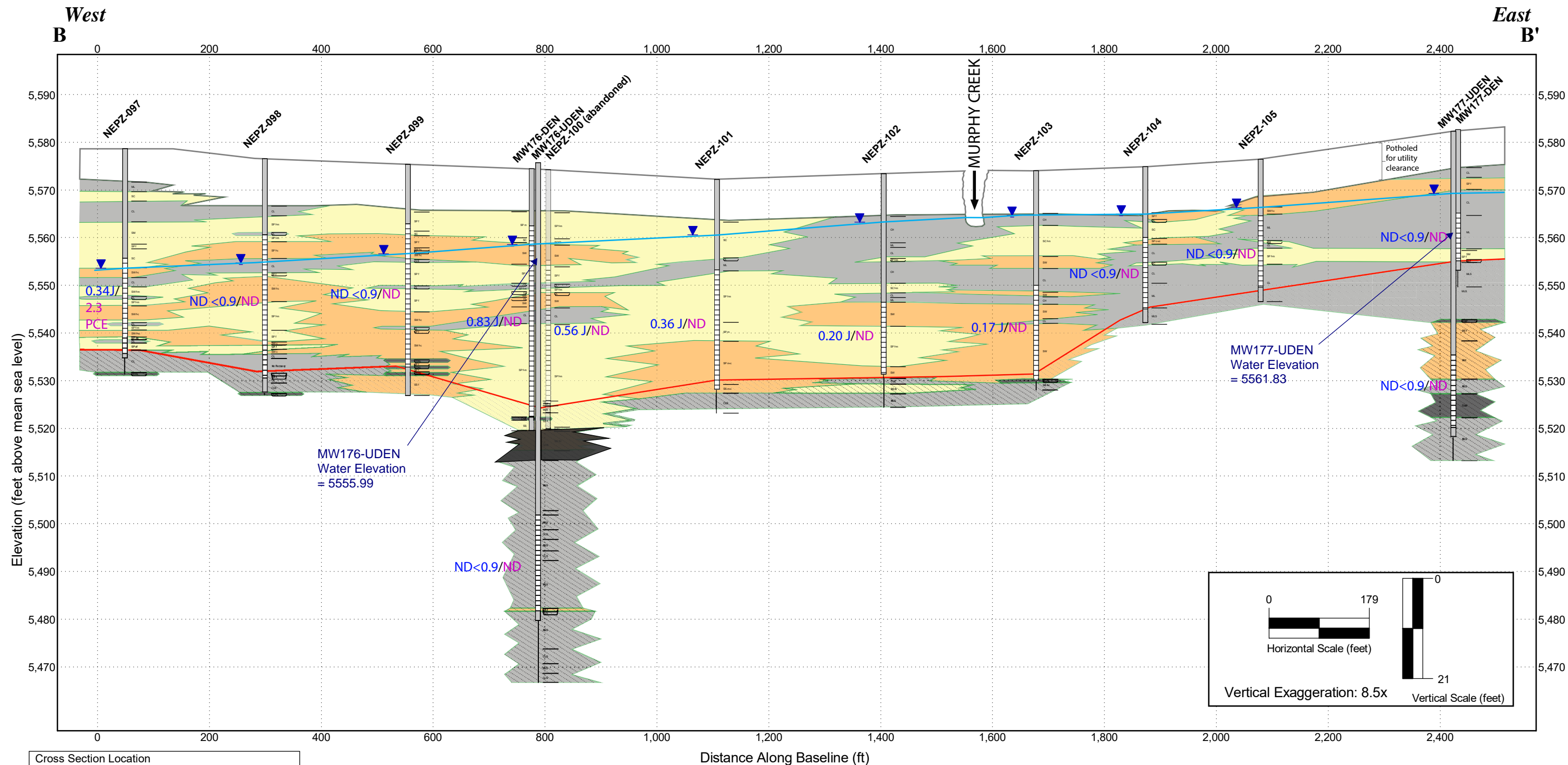






Source: Updated 1,4-Dioxane Plume Map and North End Conceptual Model, 2017 Five-Year Review Issue #7, Lowry Landfill Superfund Site, 2020

STANDARD CROSS SECTION: LOWRY LOWRY\_GINT.GPJ STANDARD\_ENVIRONMENTAL\_PROJECT.GDT 6/4/19 REV.



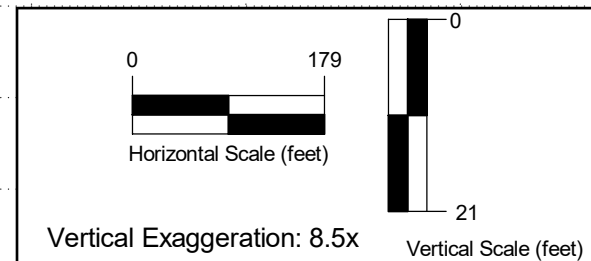
Legend:

CL = Inorganic Clay  
ML = Inorganic Silts  
SC = Clayey Sands  
SM = Silty Sands  
(f = Fine Grained)  
(m = Medium Grained)  
(c - Coarse Grained)  
SP = Poorly Graded Sands  
SW = Well Graded Sands  
CLS = Claystone  
MLS = Siltstone  
SS = Sandstone

Coarse Sands Associated With Channel Deposits  
Fine Sands Associated With Overbank Deposits  
Silt and Clays Associated With Delta Plain Deposits  
Lignite  
Well Screen

Weathered /Unweathered Upper Denver Boundary  
Lithologic Contact  
Land Surface  
Water Table Elevation (Dashed Where Inferred)  
Water Level Measured in Weathered Upper Denver Well on April 2019  
Unweathered Upper Denver

0.00 1,4- Dioxane concentration in ug/L  
1.5 PCE - Tetrachloroethene concentration in ug/L  
J Estimated 1,4-Dioxane concentration  
ND Not Detected above Practical Quantitation Limit (PQL)  
Approximate Limits 1,4-Dioxane Concentration Greater than Site's Performance Standard of 0.9 ug/L in Groundwater (dashed where inferred)



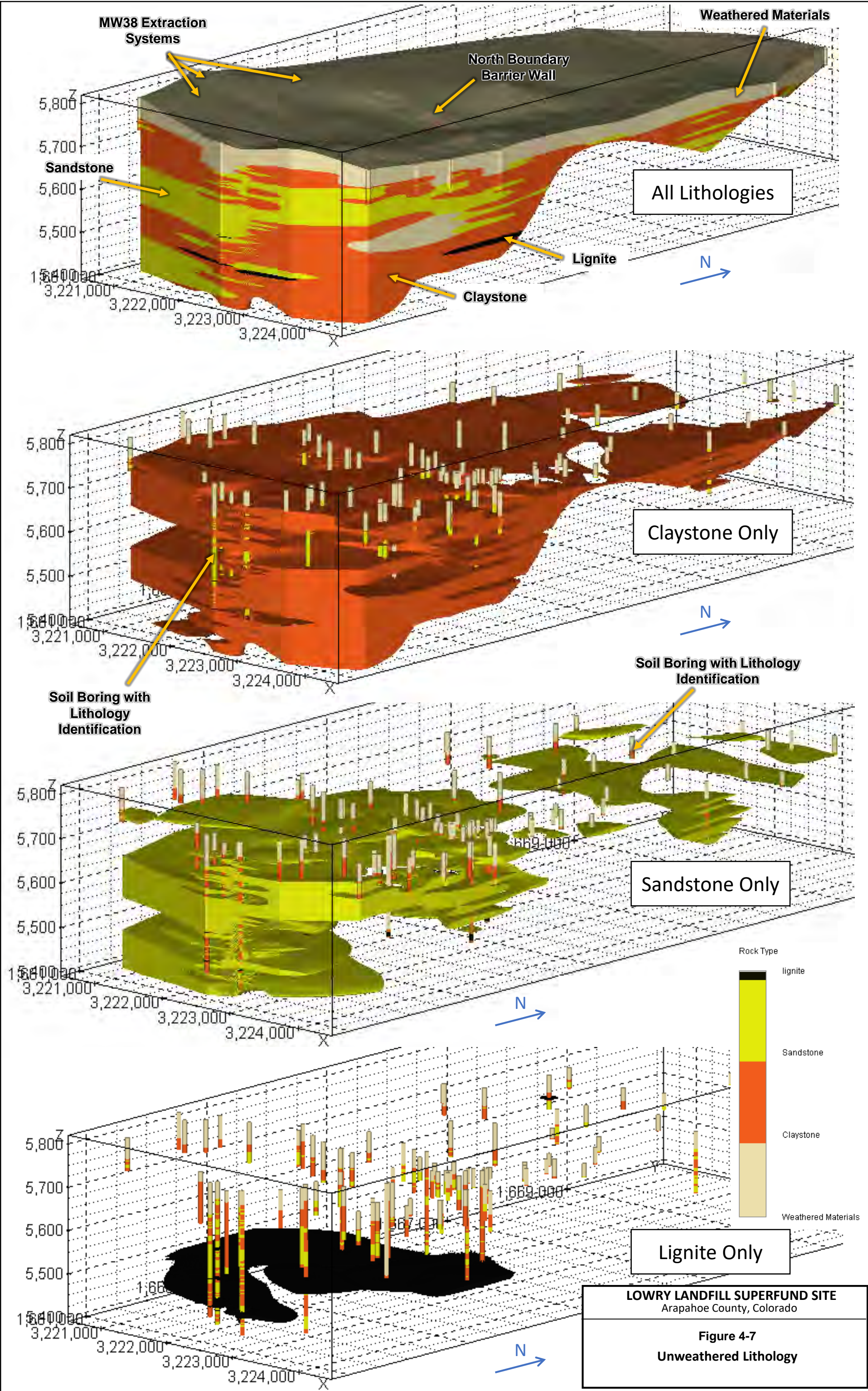
Source: Updated 1,4-Dioxane Plume Map and North End Conceptual Model, 2017 Five-Year Review Issue #7, Lowry Landfill Superfund Site, 2020

LOWRY LANDFILL SUPERFUND SITE  
Arapahoe County, Colorado

Figure 4-6  
Cross Section B-B'  
Mississippi Avenue









Era	System or Period	Series	Regional Geologic Unit	Local or sub-units	Regional Aquifer Designation	Site Hydrostratigraphic Unit
Cenezoic	Quaternary	Recent and Pleistocene	Quaternary surficial deposits	Stream channel, floodplain and terrace deposits; eolian sand, etc	Alluvial/shallow systems	alluvium and weathered Dawson
	Tertiary	Paleocene	Dawson Arkose	(separation layer) →	Dawson aquifer	unweathered Dawson
					Denver aquifer	upper Denver
						lignite layer
Mesozoic	Cretaceous	upper Cretaceous	Denver Formation	(lignite layer at top)		

# LOWRY LANDFILL SUPERFUND SITE

Arapahoe County, Colorado

**Figure 4-8**  
**Generalized Hydrostratigraphic Column**  
**of Geologic and Aquifer Designations**

Source: Figure C-3 (EPA, 2017)

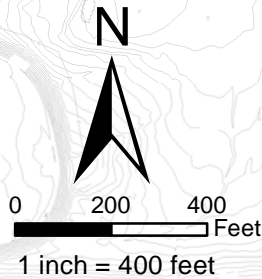


Note: All concentrations are dissolved fraction except at location NBBW and NTES are total.

Legend

- WD/UNWD
- ALLUVIUM
- ALLUVIUM/WD
- LIGNITE
- Unweathered Dawson
- UPPER DENVER
- Weathered Dawson
- NO GEOLOGIC LOG
- Compliance Well

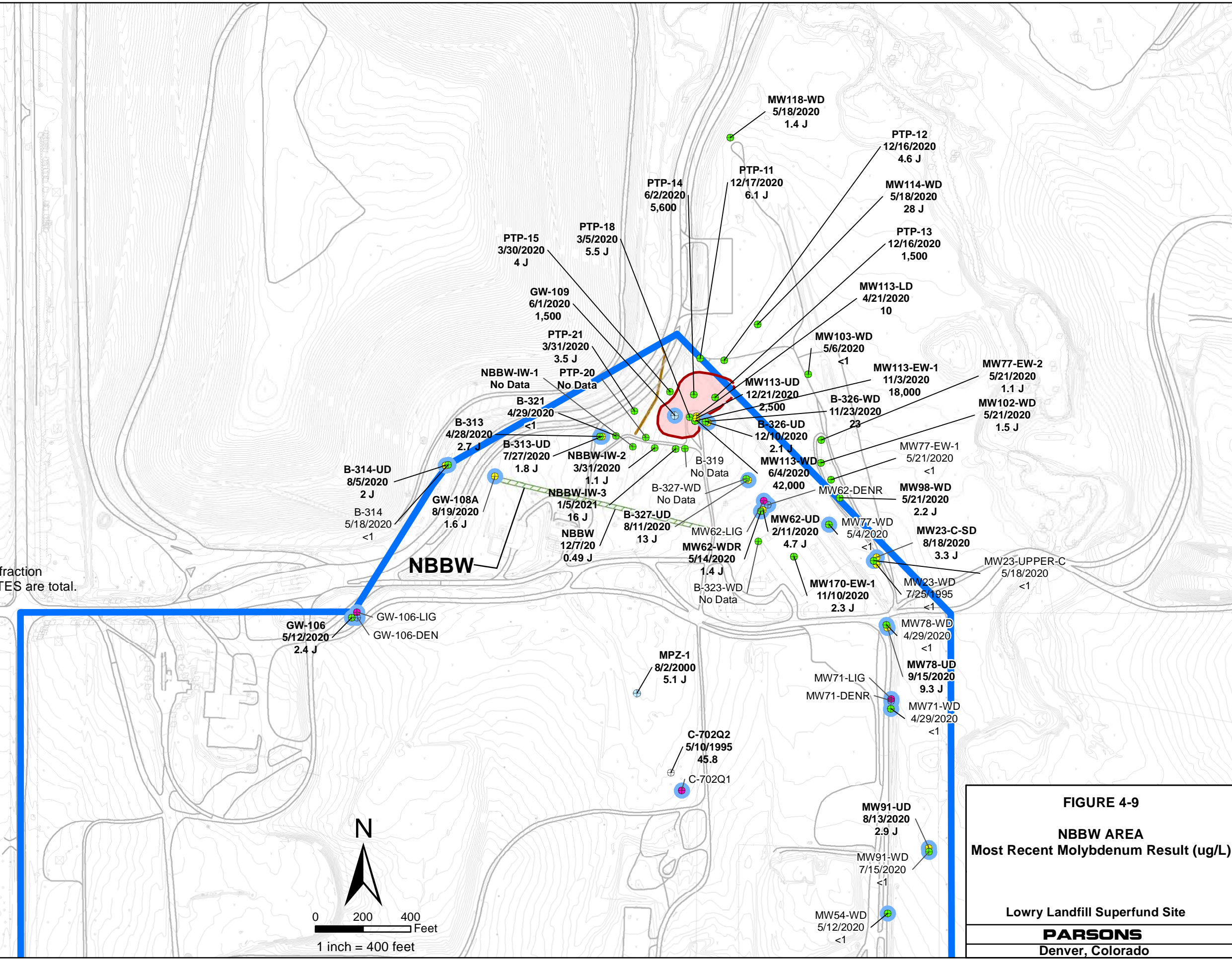
- Superfund Site Boundary
- Molybdenum Concentration  $\geq 210$  ug/L
- NBBW



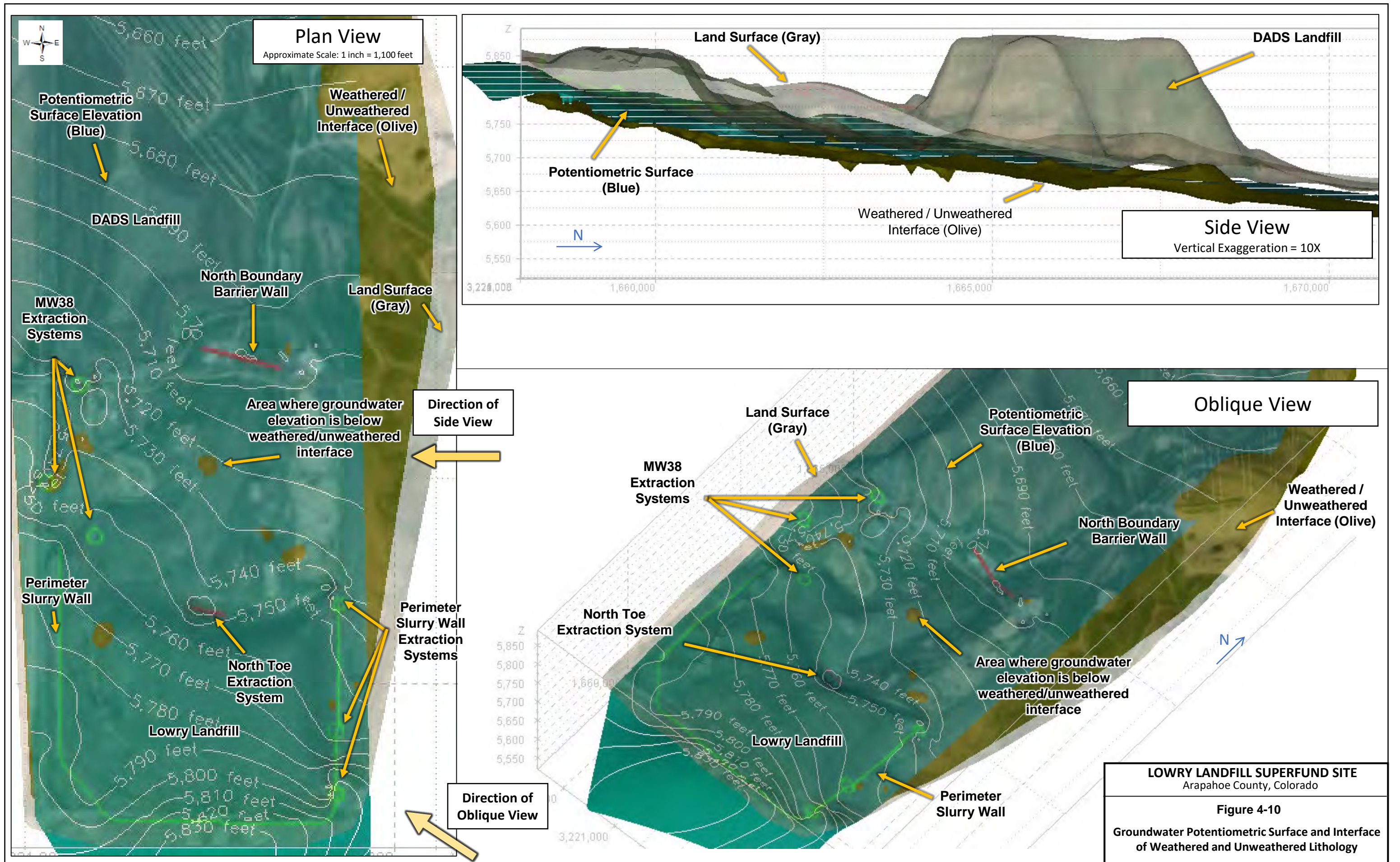
**FIGURE 4-9**  
**NBBW AREA**  
**Most Recent Molybdenum Result (ug/L)**

Lowry Landfill Superfund Site

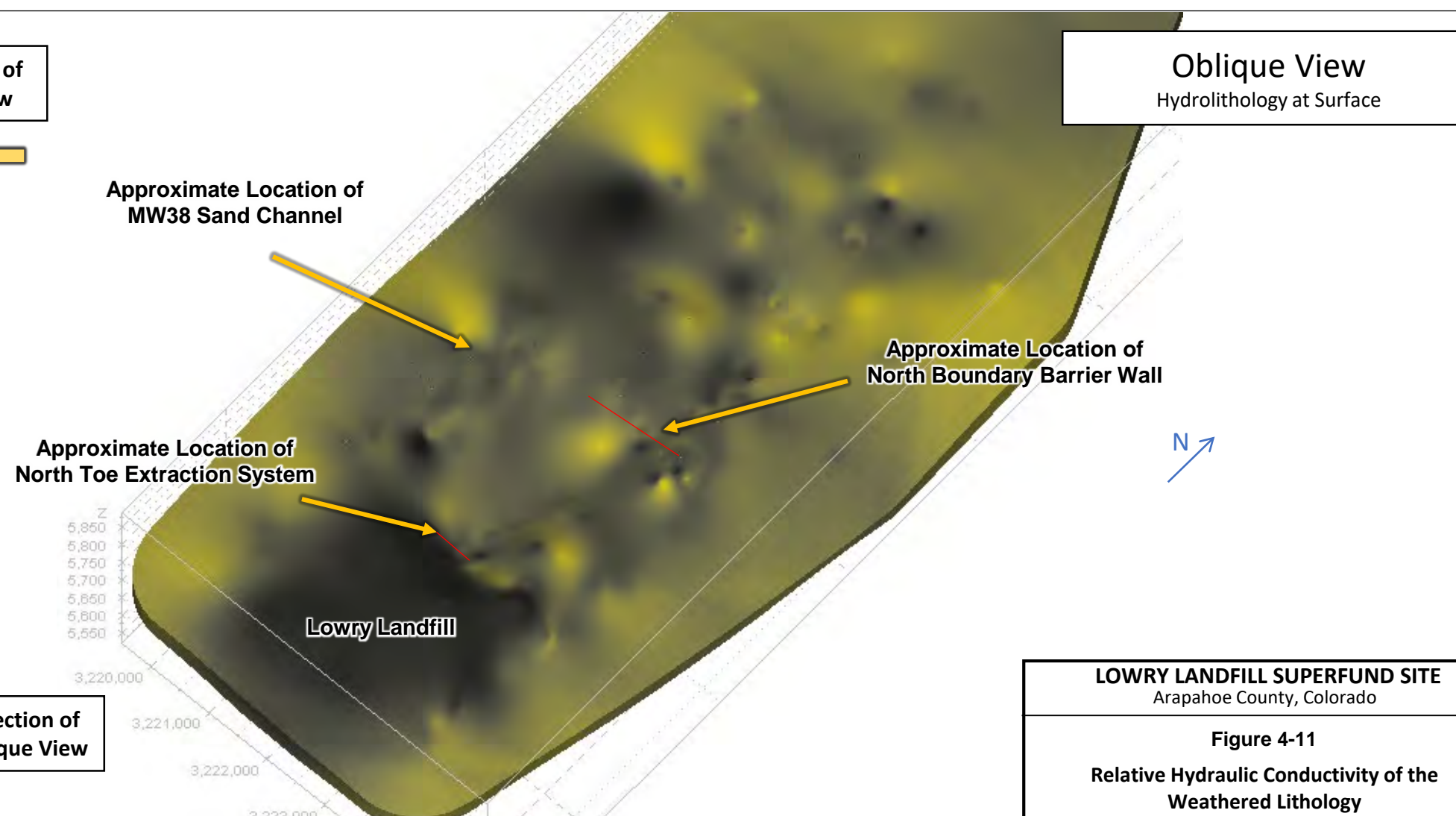
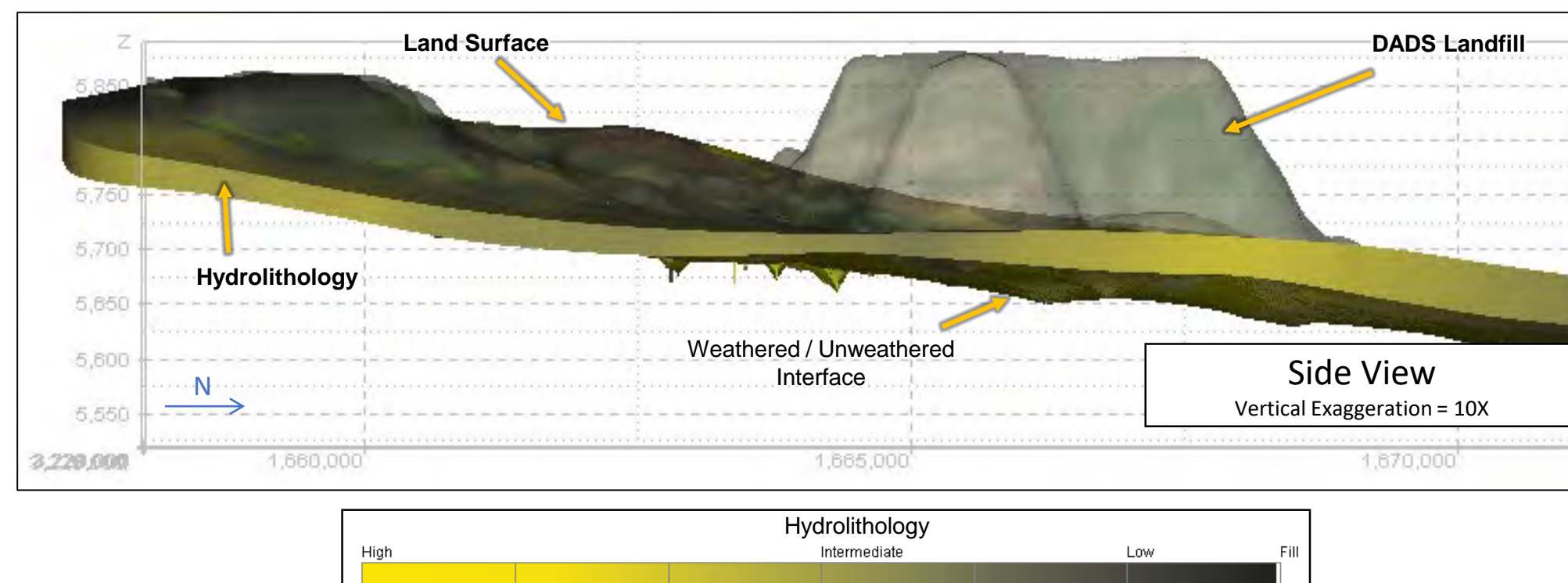
**PARSONS**  
Denver, Colorado







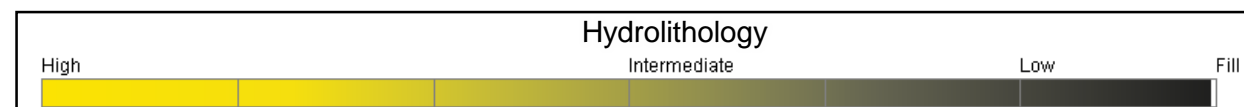
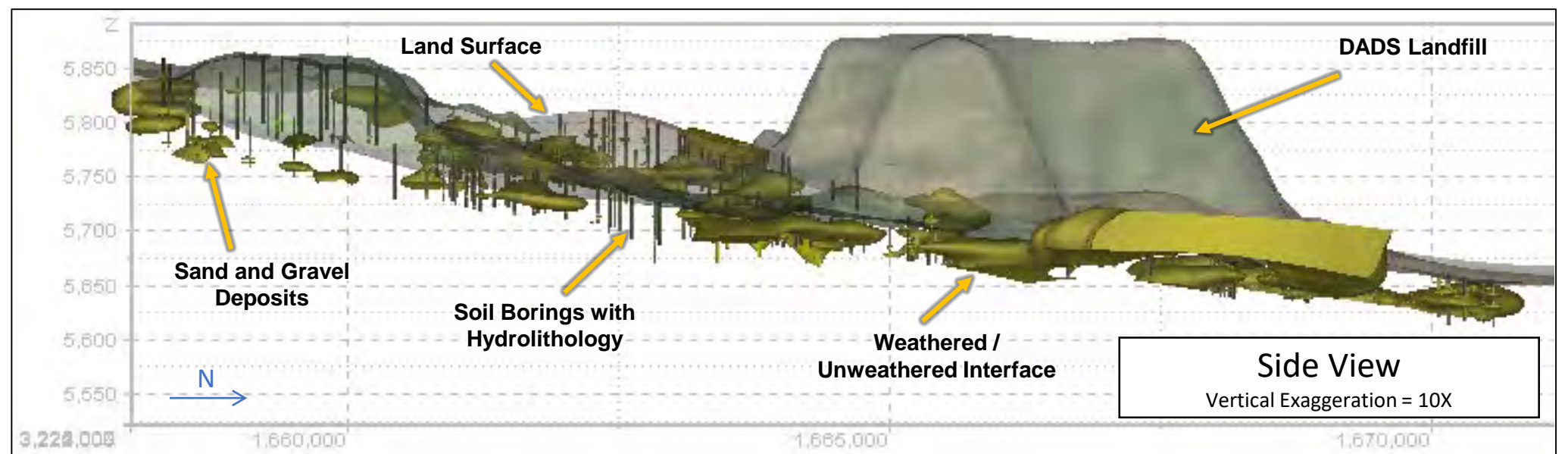




**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

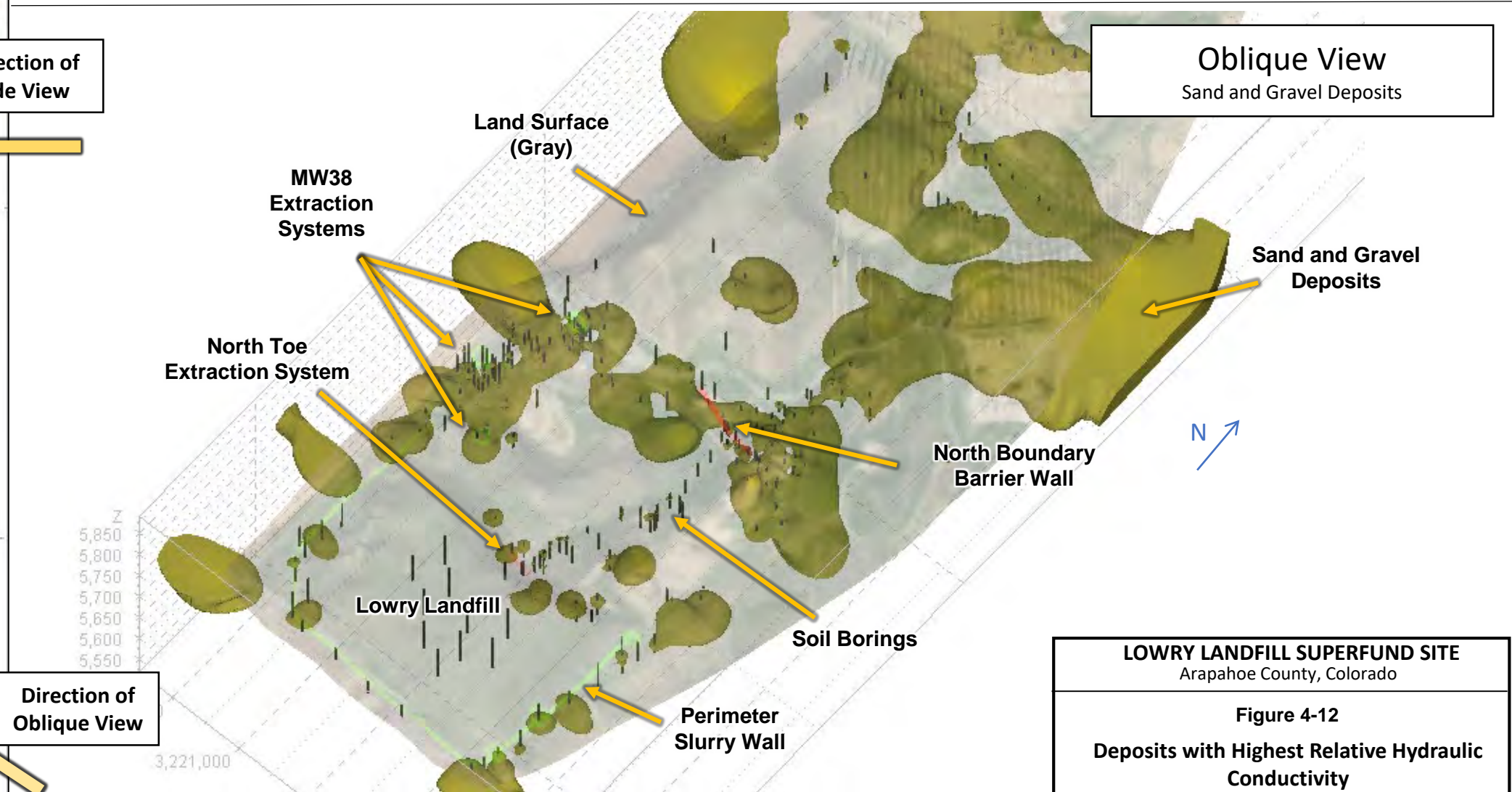
**Figure 4-11**  
Relative Hydraulic Conductivity of the  
Weathered Lithology





Direction of Side View

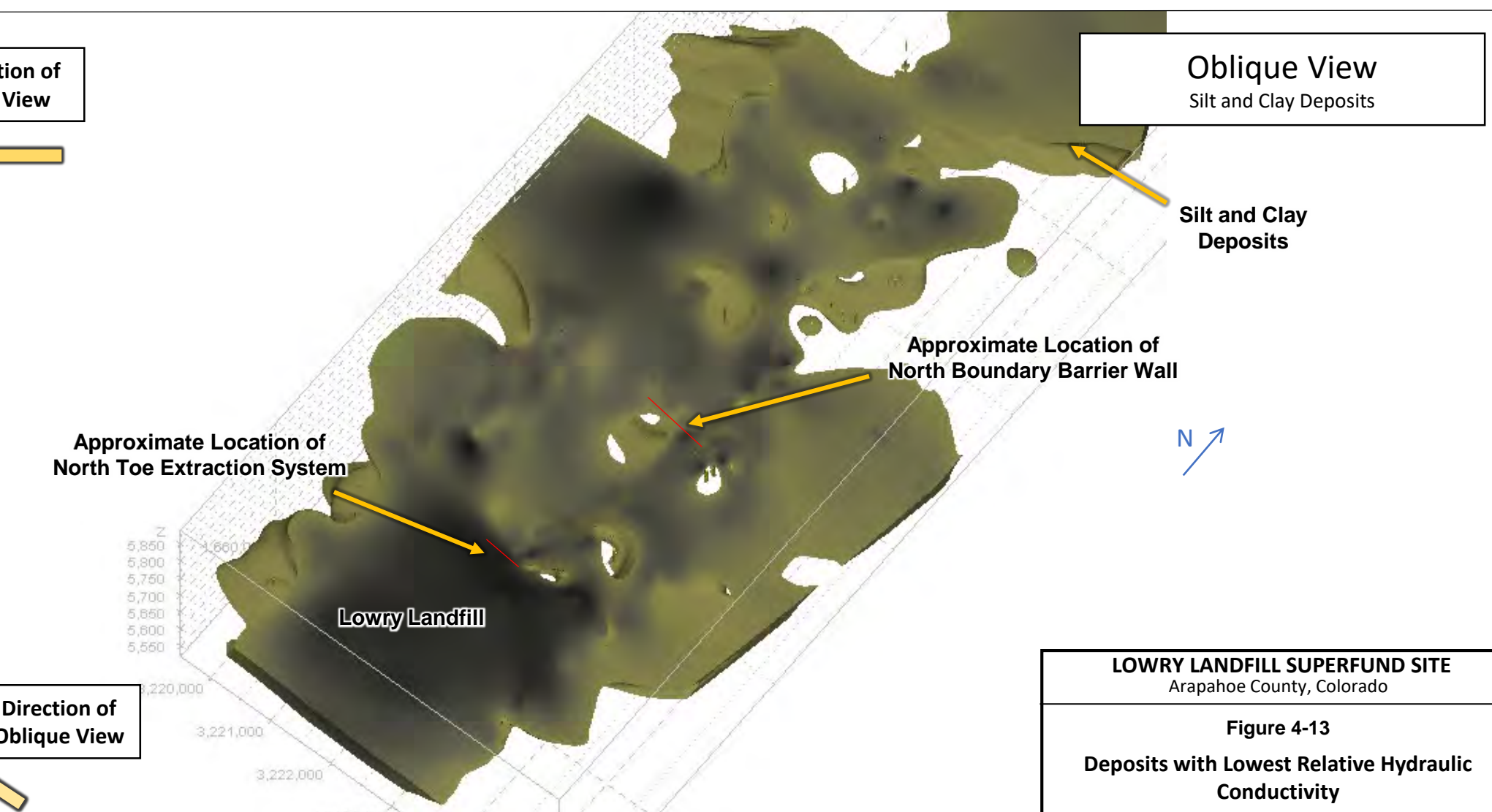
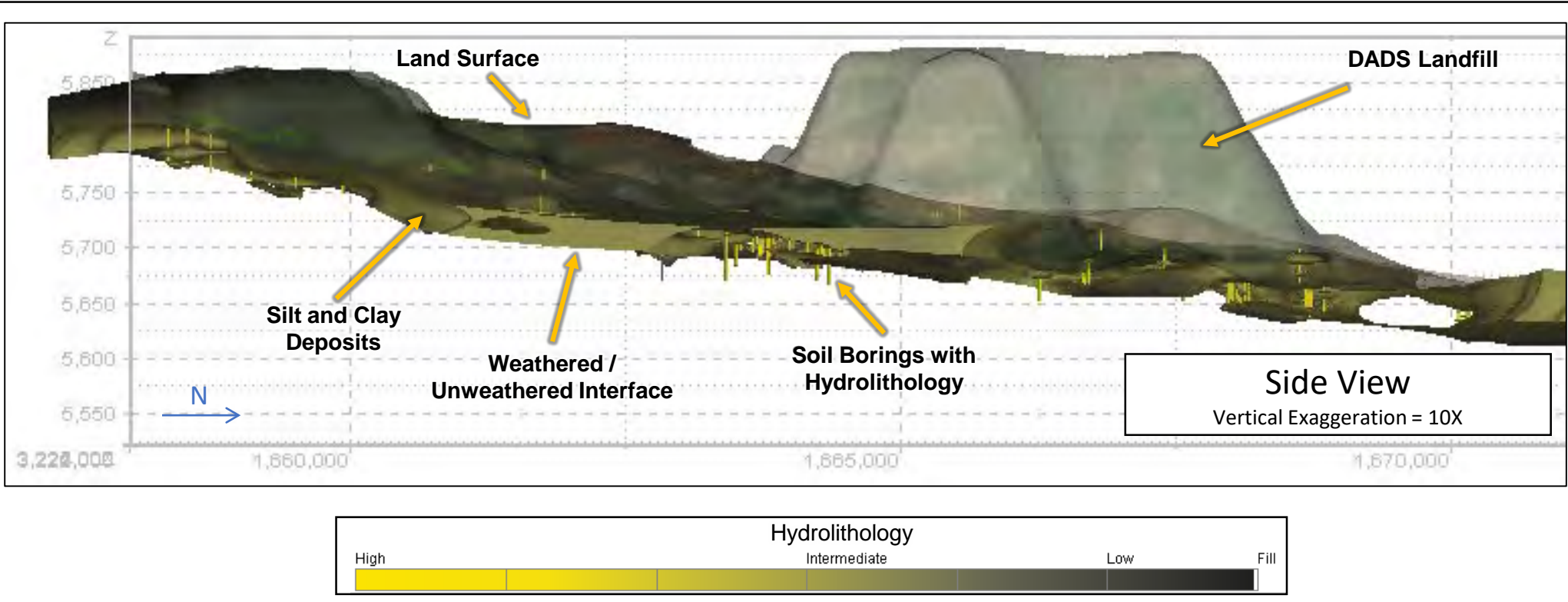
Direction of Oblique View



**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 4-12**  
Deposits with Highest Relative Hydraulic Conductivity

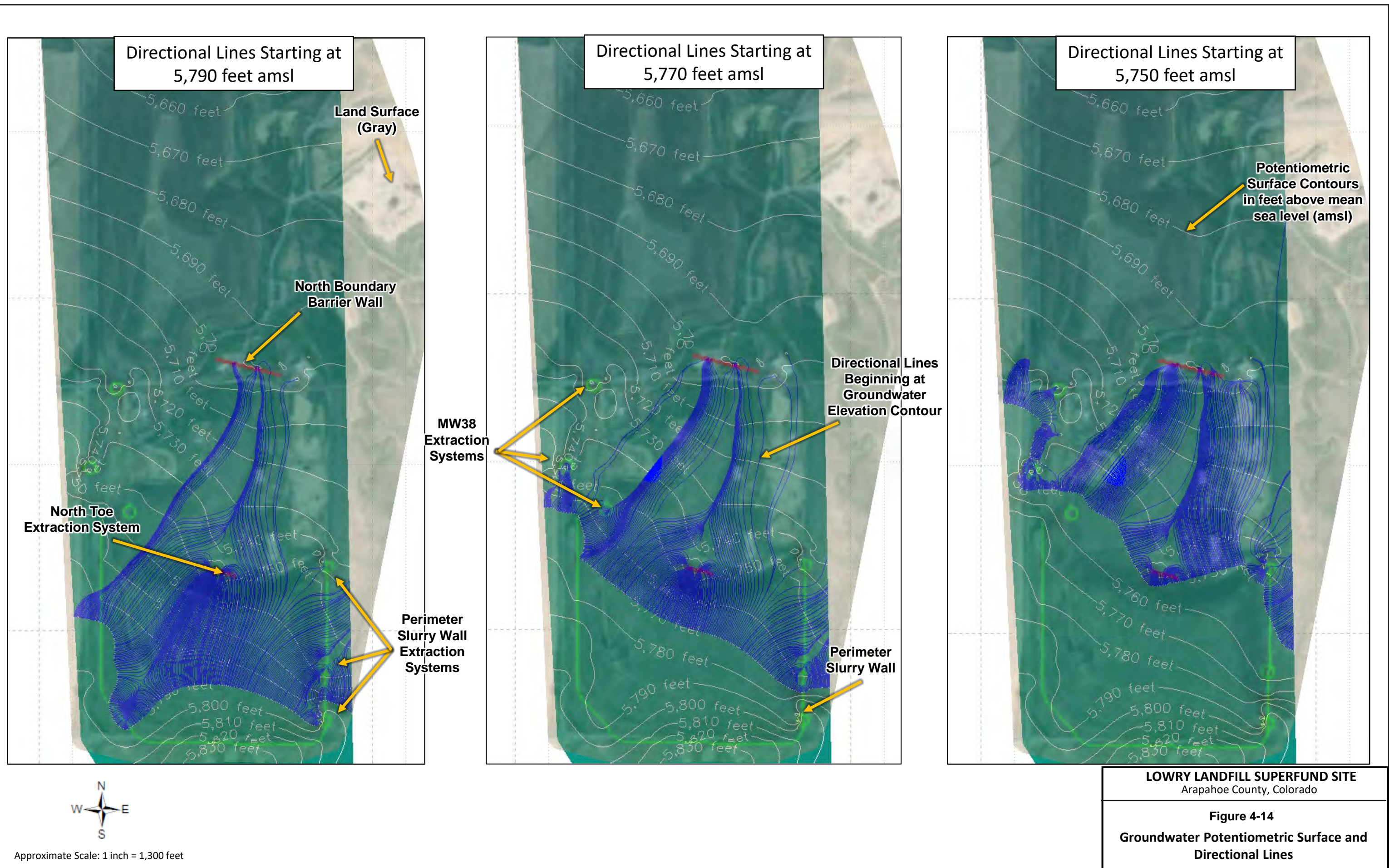




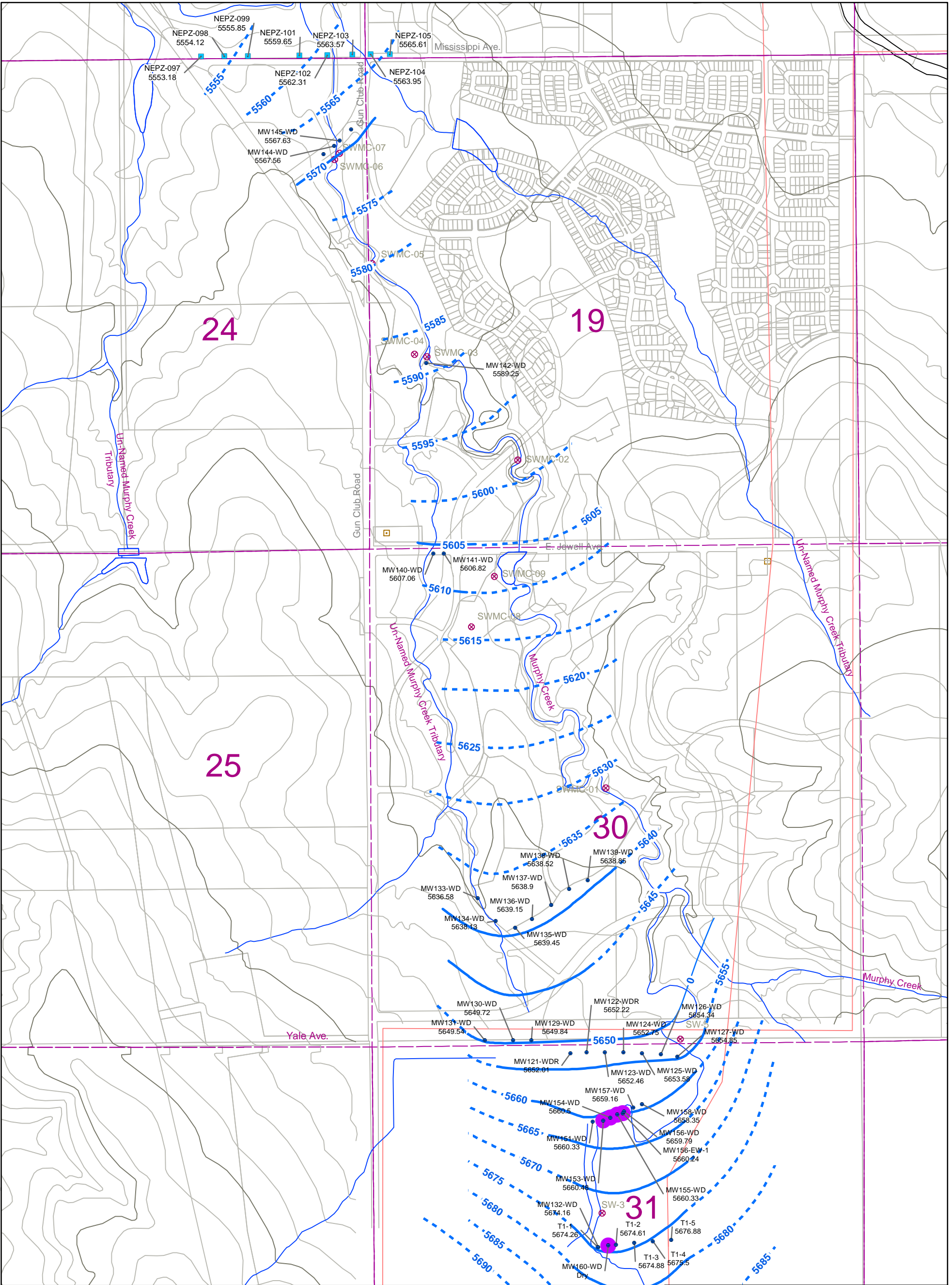
**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 4-13**  
Deposits with Lowest Relative Hydraulic Conductivity



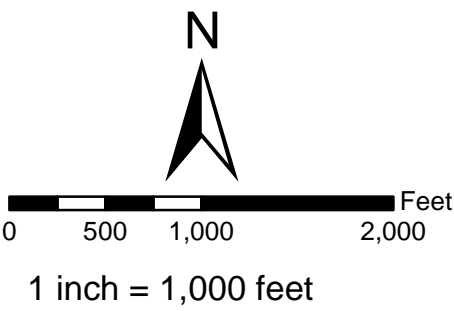






Legend

- Groundwater Extraction Well
- Groundwater Monitoring Well
- Domestic Well Location
- Surface Water Sample Location
- Piezometer Location
- Dry Water Level Below Base of Screen



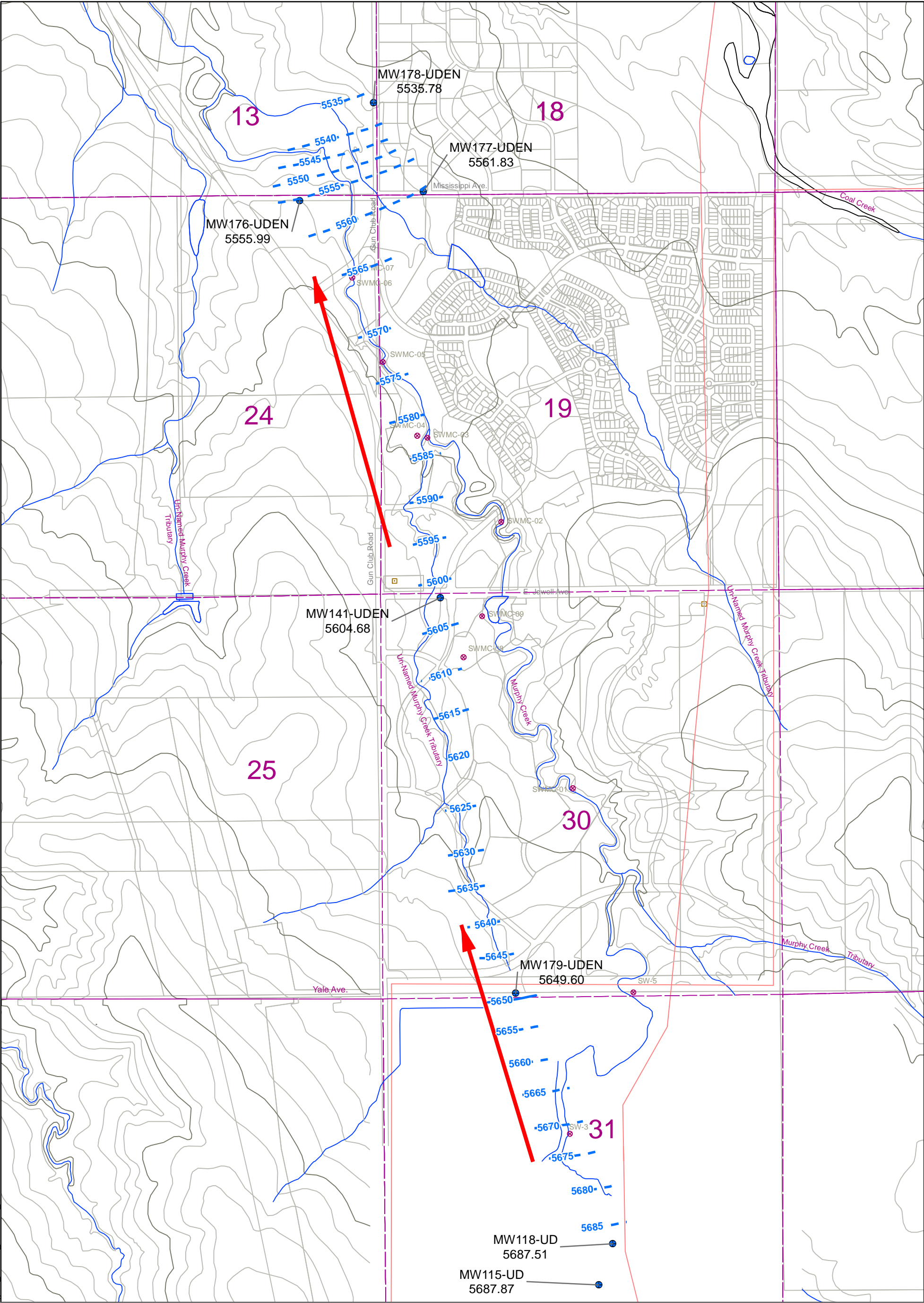
Source: Figure 4.24 (Parsons 2019)

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 4-15**  
**Sections 19 and 30 Weathered**  
**Dawson/Weathered Upper Denver**  
**Potentiometric Surface July 2018**

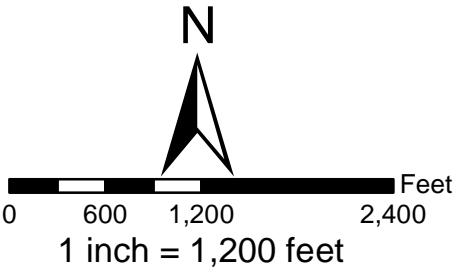


S:\ESMajProj\LWRY\LNFL\Steven\FGIS\Steven\_Fig3-2\_UNWD\_Sec1930\_WaterLevelsQ19.mxd lxb 6/18/2019



**Legend**

- Groundwater Flow Direction
- Groundwater Extraction Well
- Groundwater Monitoring Well
- Domestic Well Location
- Surface Water Sample Location
- Piezometer Location
- Dry
- Water Level Below Base of Screen



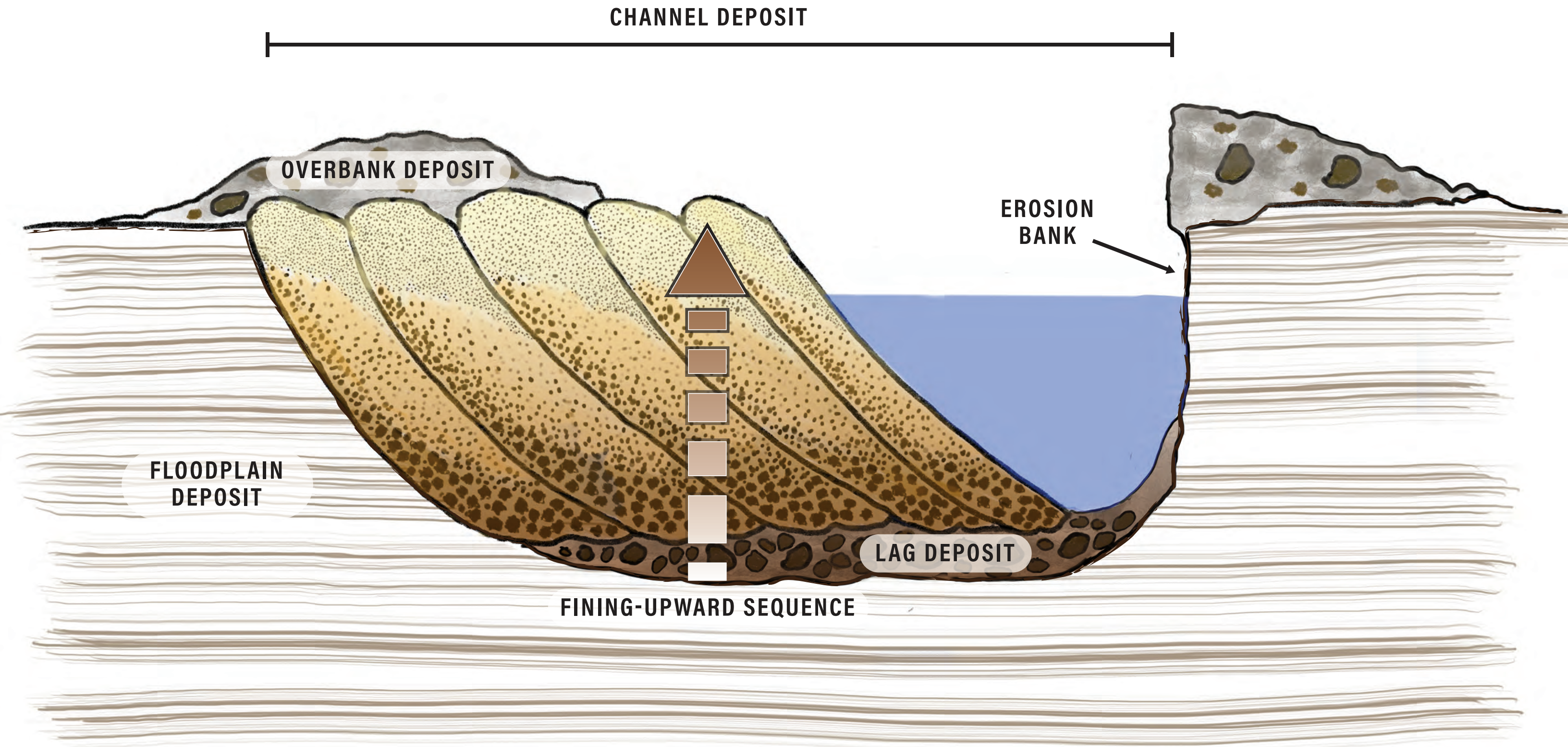
**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 4-16**  
**Sections 19 and 30**  
**Unweathered Geologic Unit**  
**Potentiometric Surface**  
**April 2019**



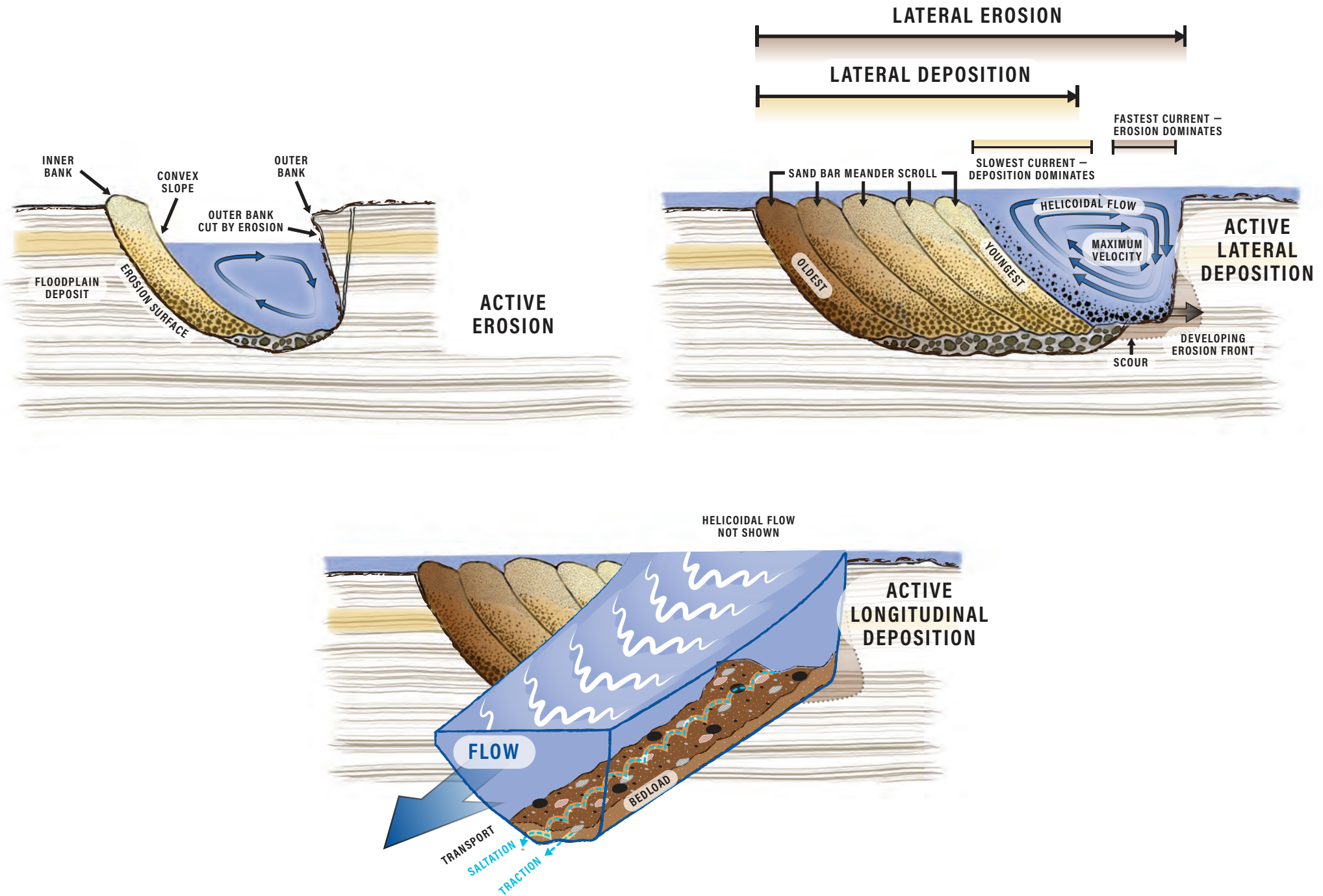
# 4-1 Fluvial Deposits

## *Meandering Stream*



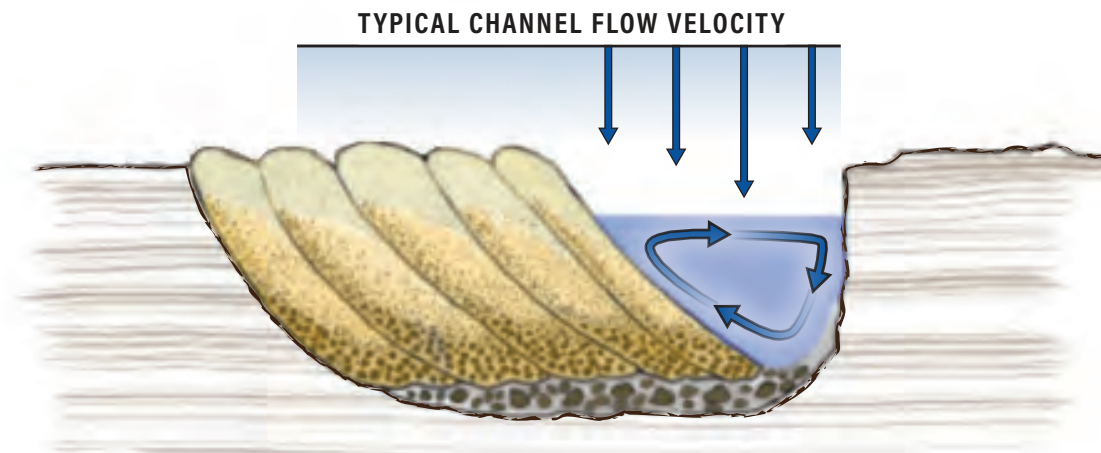


## 4-2 (a) Channel Sand Deposits / Bank Erosion

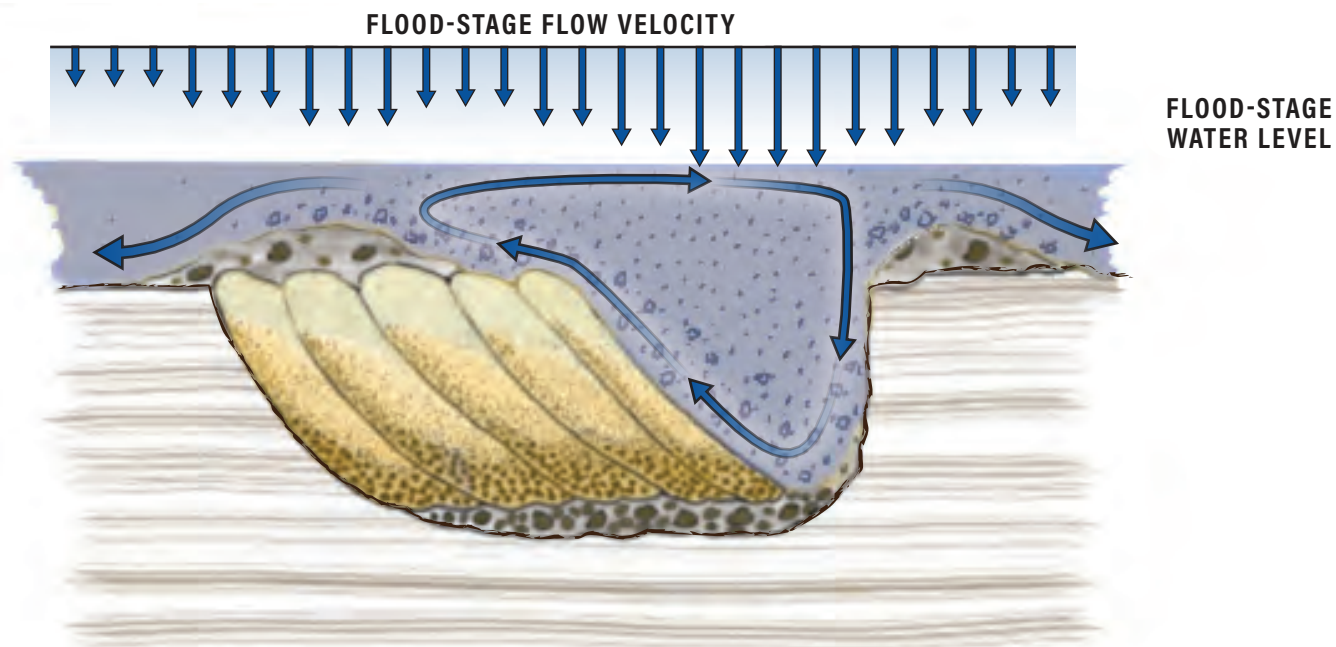


## 4-2 (b) Overbank Deposits / Floodplain Deposits

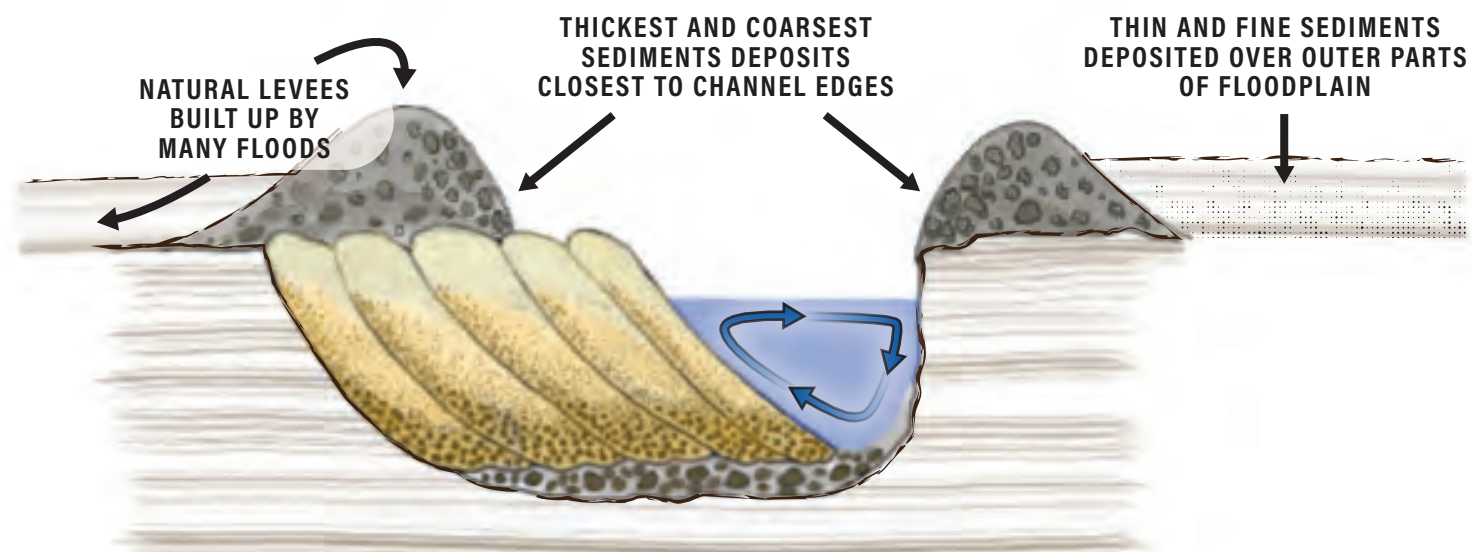
*Before Flood*



*During Flood*

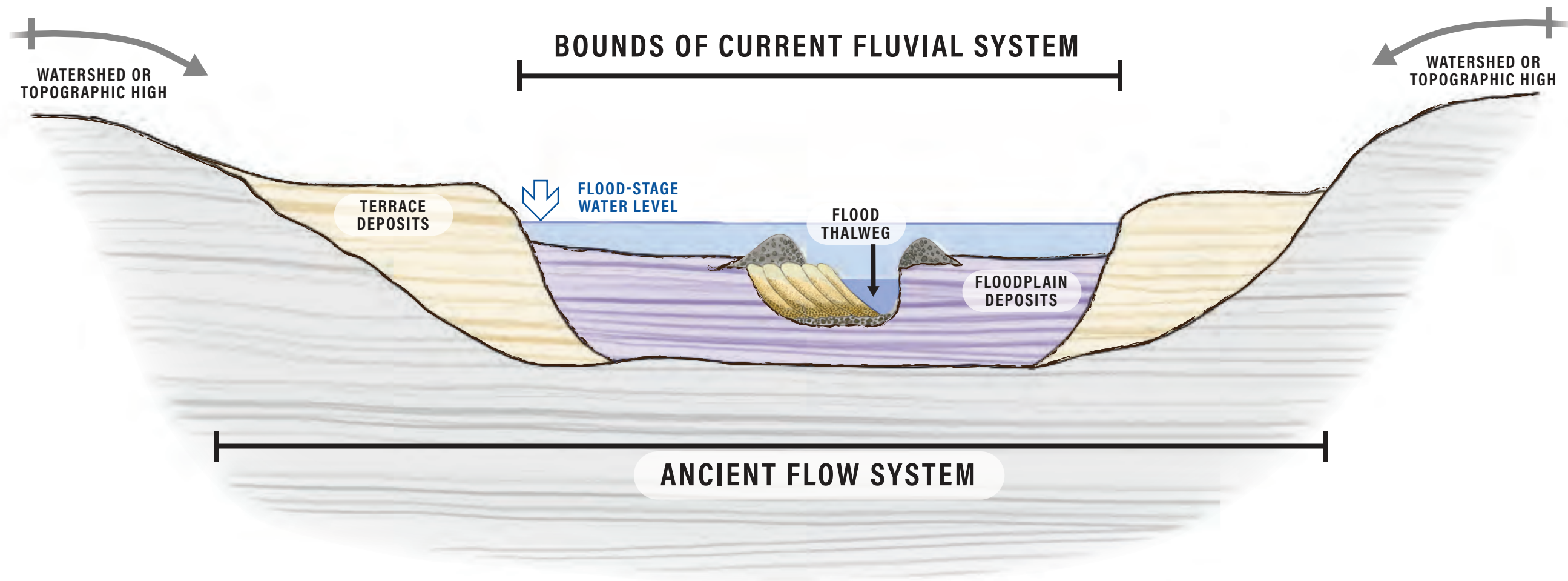


*After Flood*

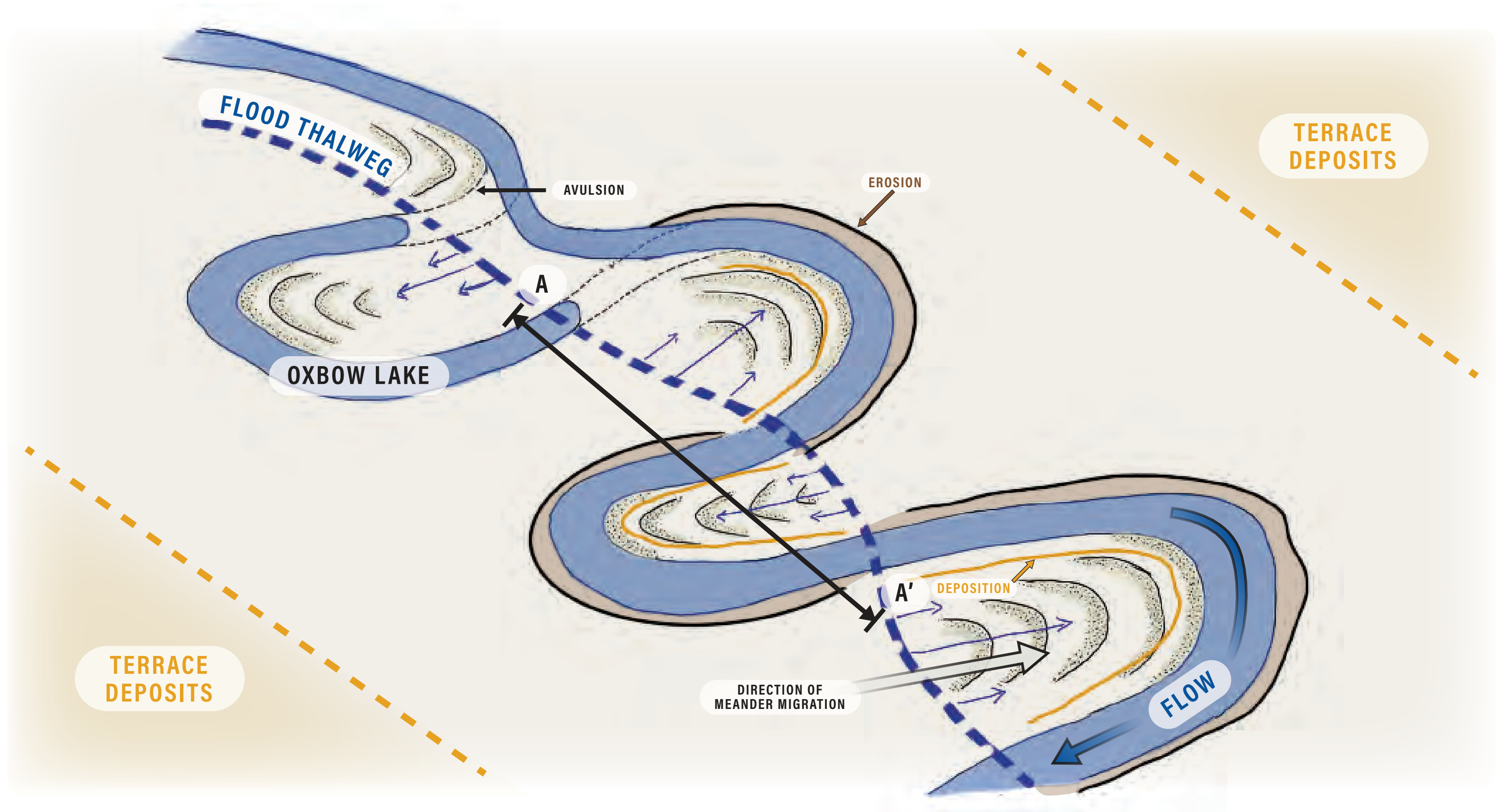




## 4-3 (a) Floodplain Boundary

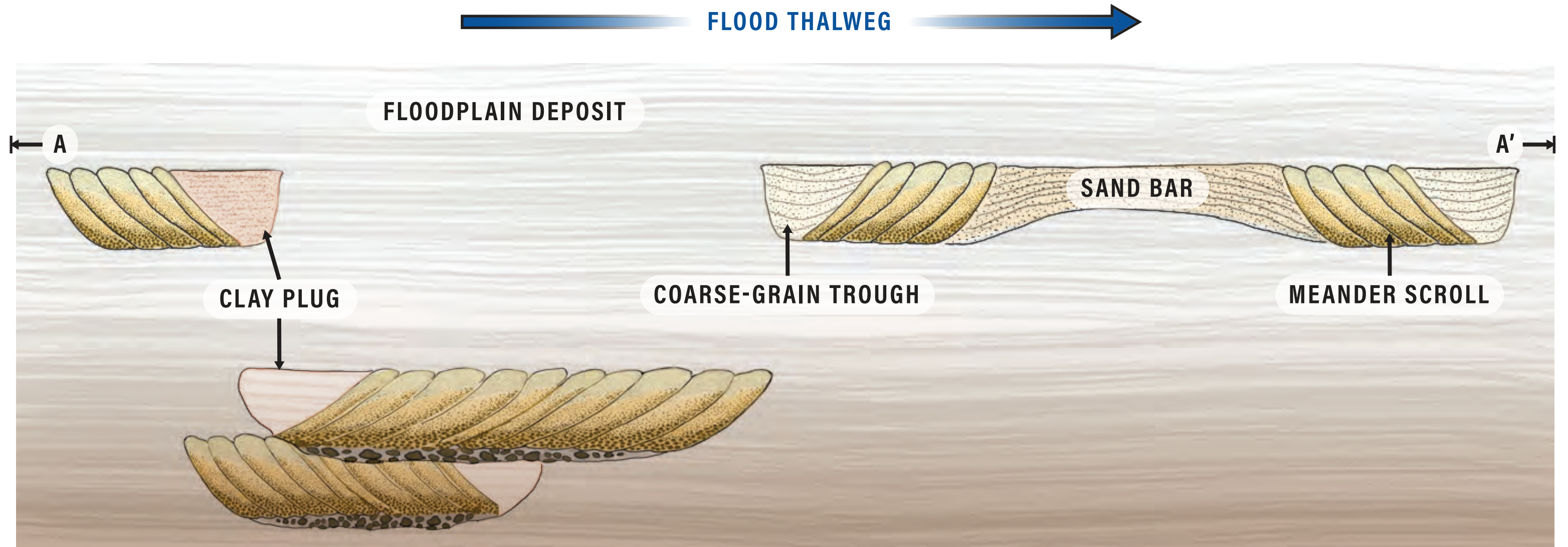


## 4-3 (b) Lateral Paralleling of Ancient Flow Systems



## 4-3 (c) Channel Deposits

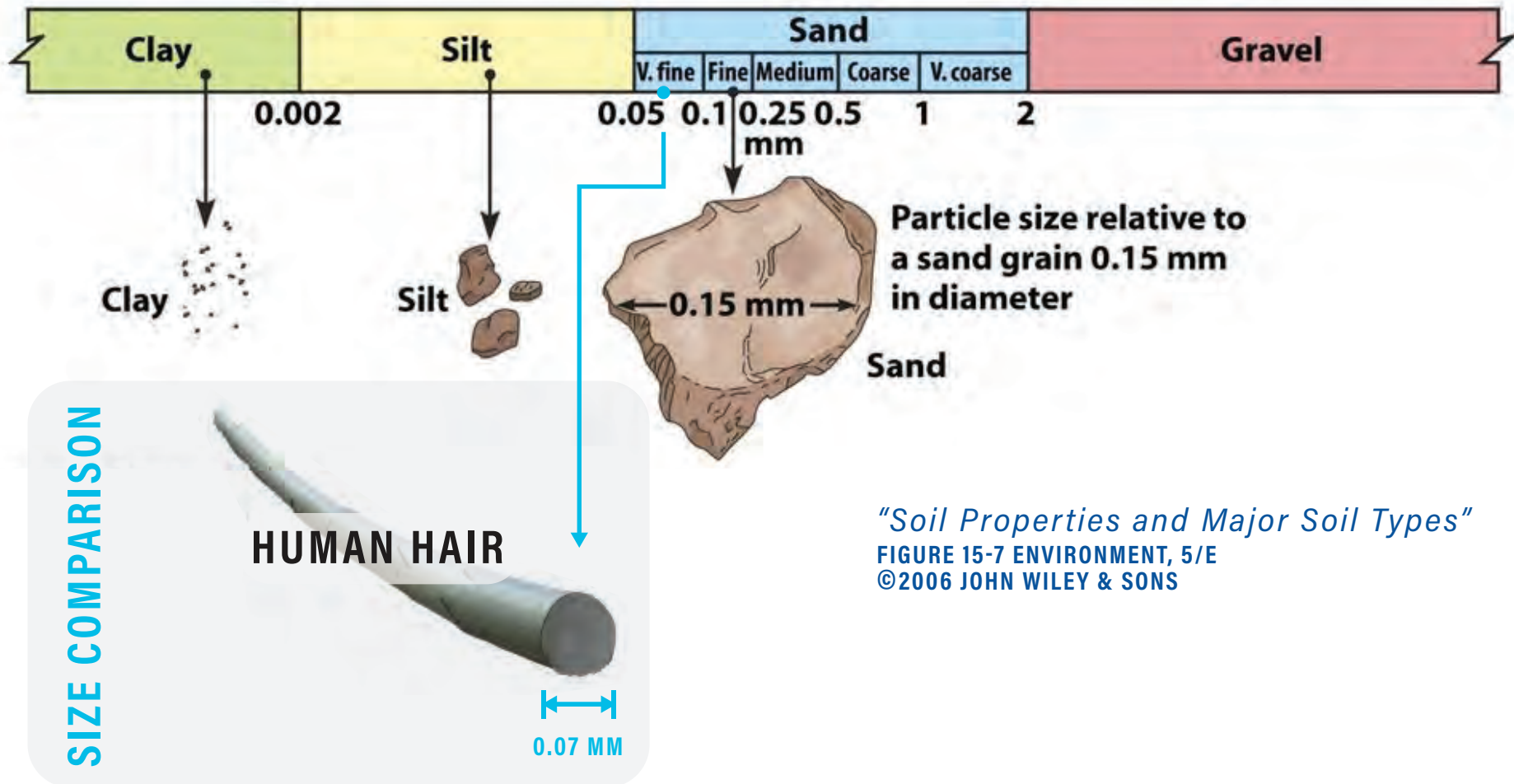
*Longitudinal to Flood Thalweg (A-A')*





## 4-4 (a) Soil Textures

### *Sand, Silt, and Clay*



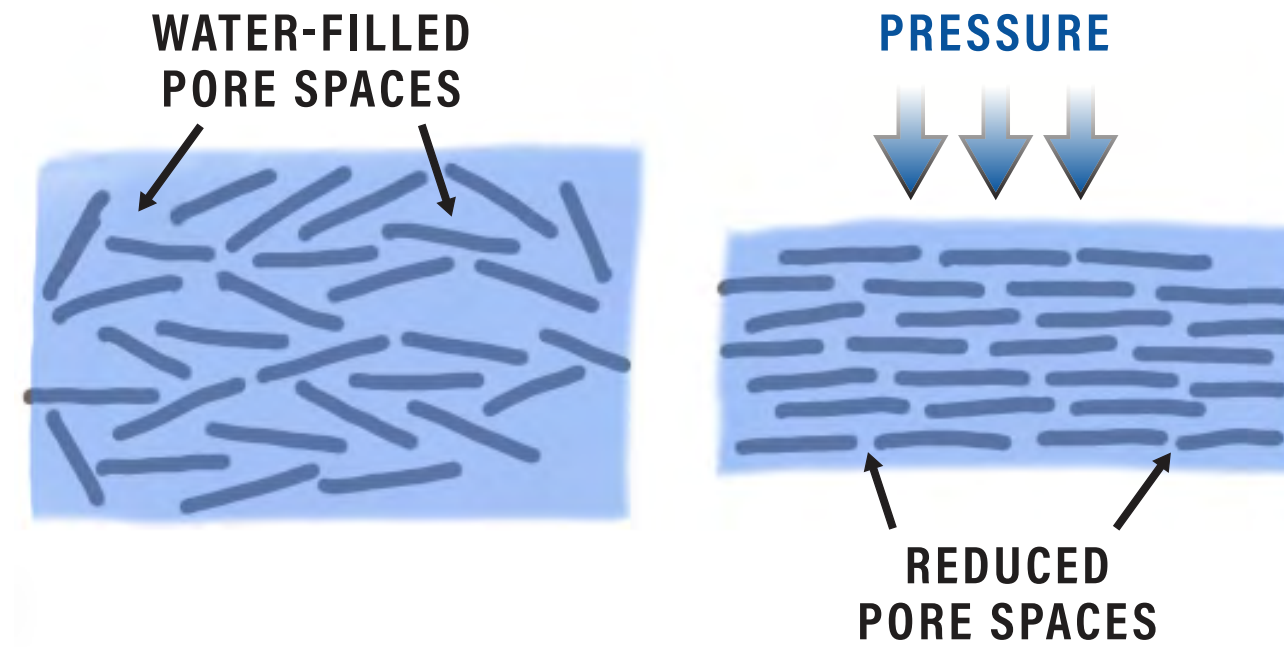
*"Soil Properties and Major Soil Types"*

FIGURE 15-7 ENVIRONMENT, 5/E

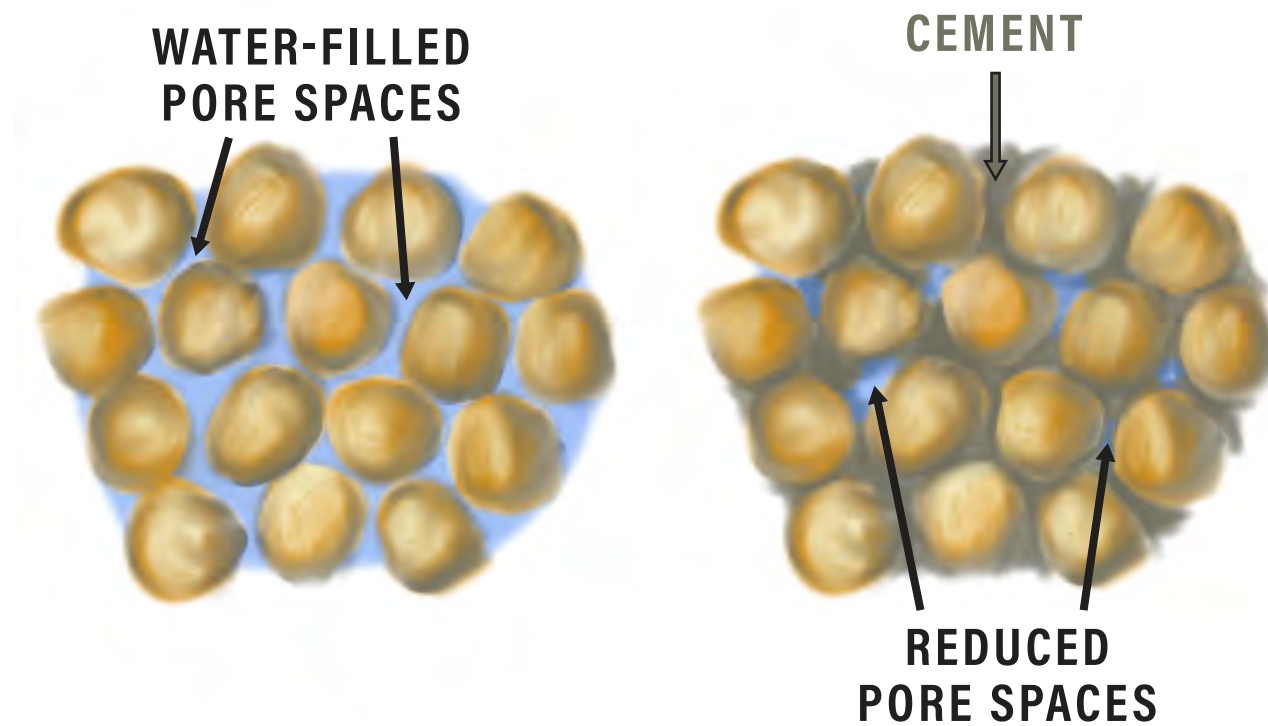
©2006 JOHN WILEY & SONS

## 4-4 (b) Compaction and Cementation

*Compaction  
(Fine-grained)*

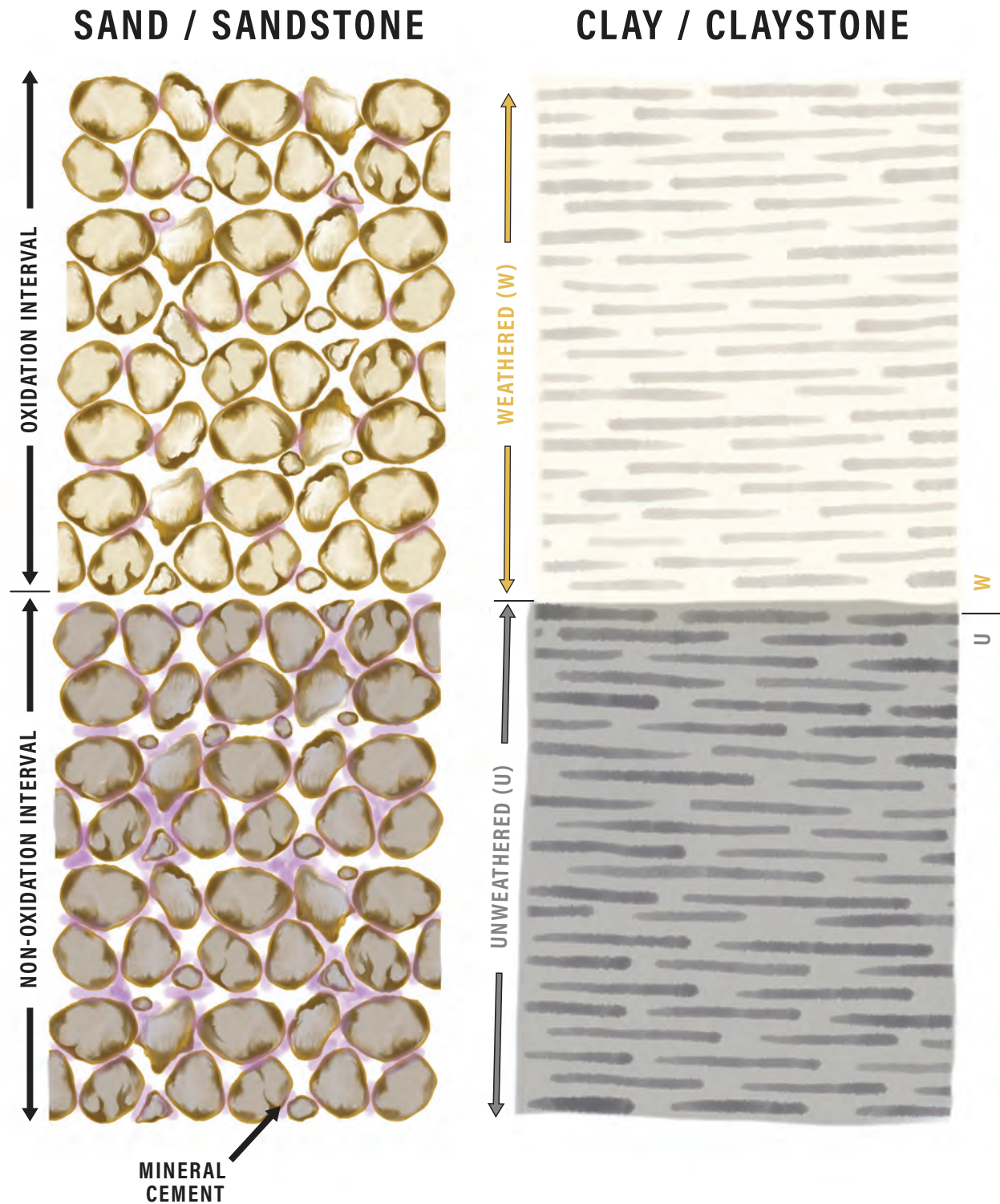


*Cementation  
(Coarse-grained)*



# 4-5 Weathering

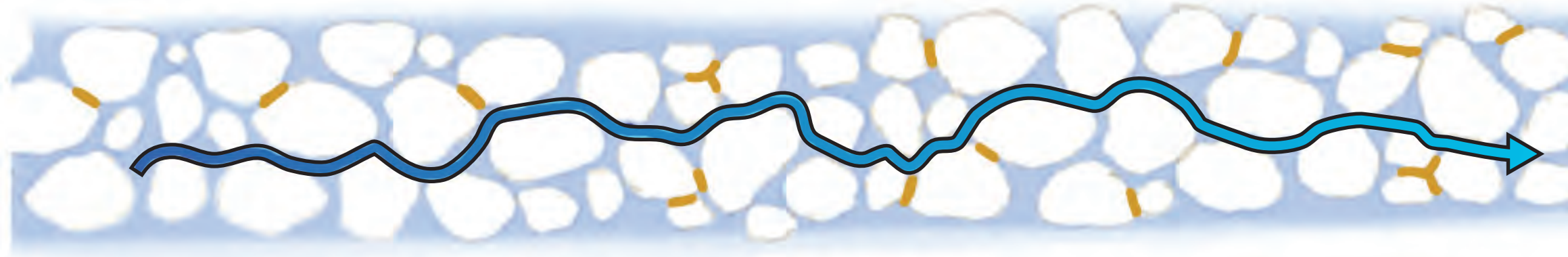
## *Coarse- and Fine-grained Lithologies*



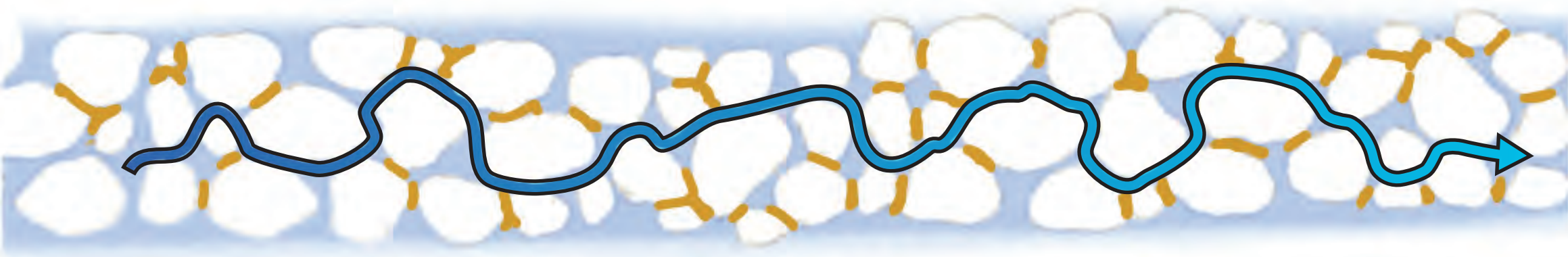


## 4-6 Flow Path through Dawson Sands and Denver Sandstone

*Weathered Dawson Sands*



*Unweathered Dawson Sands*

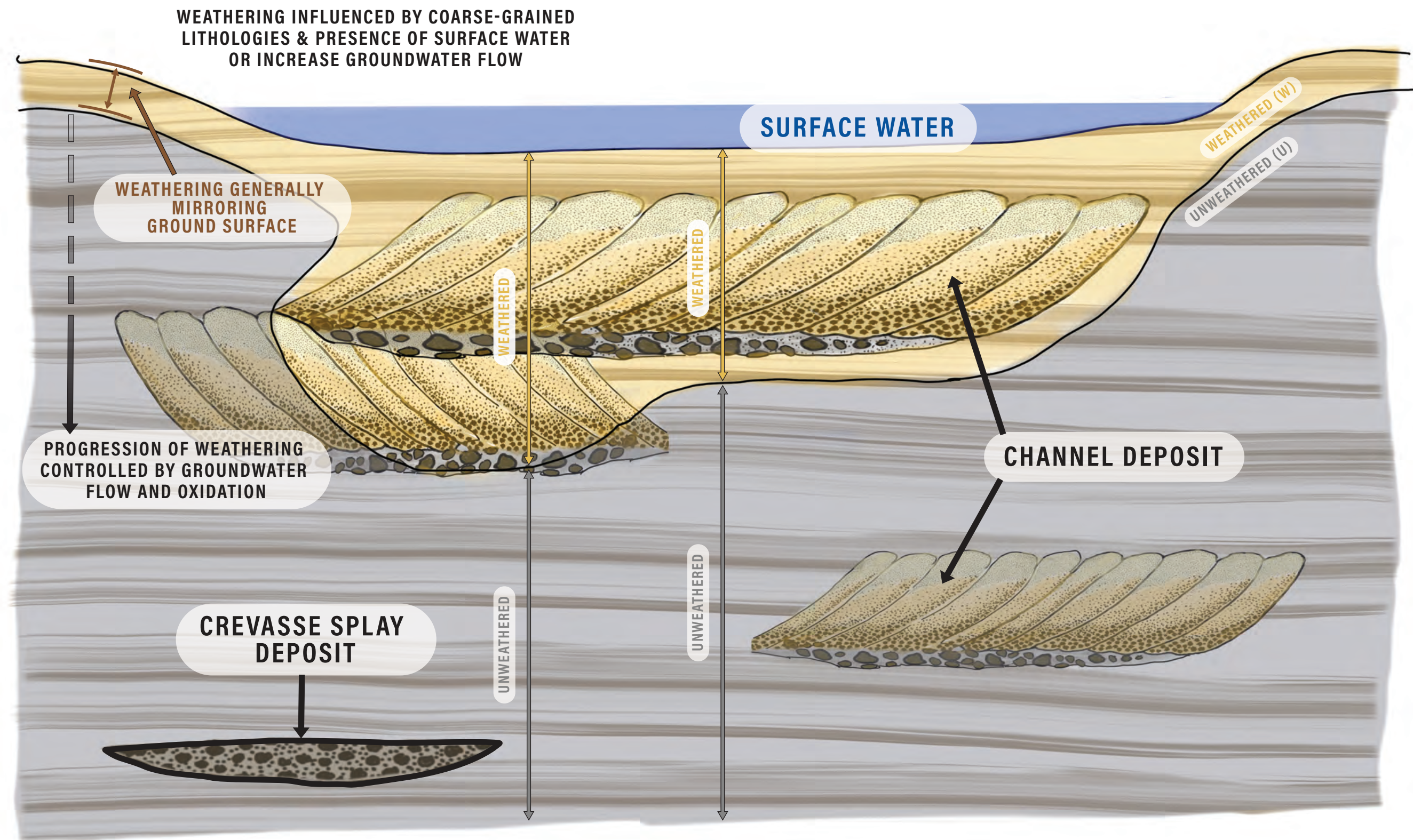


*Denver Sandstones*





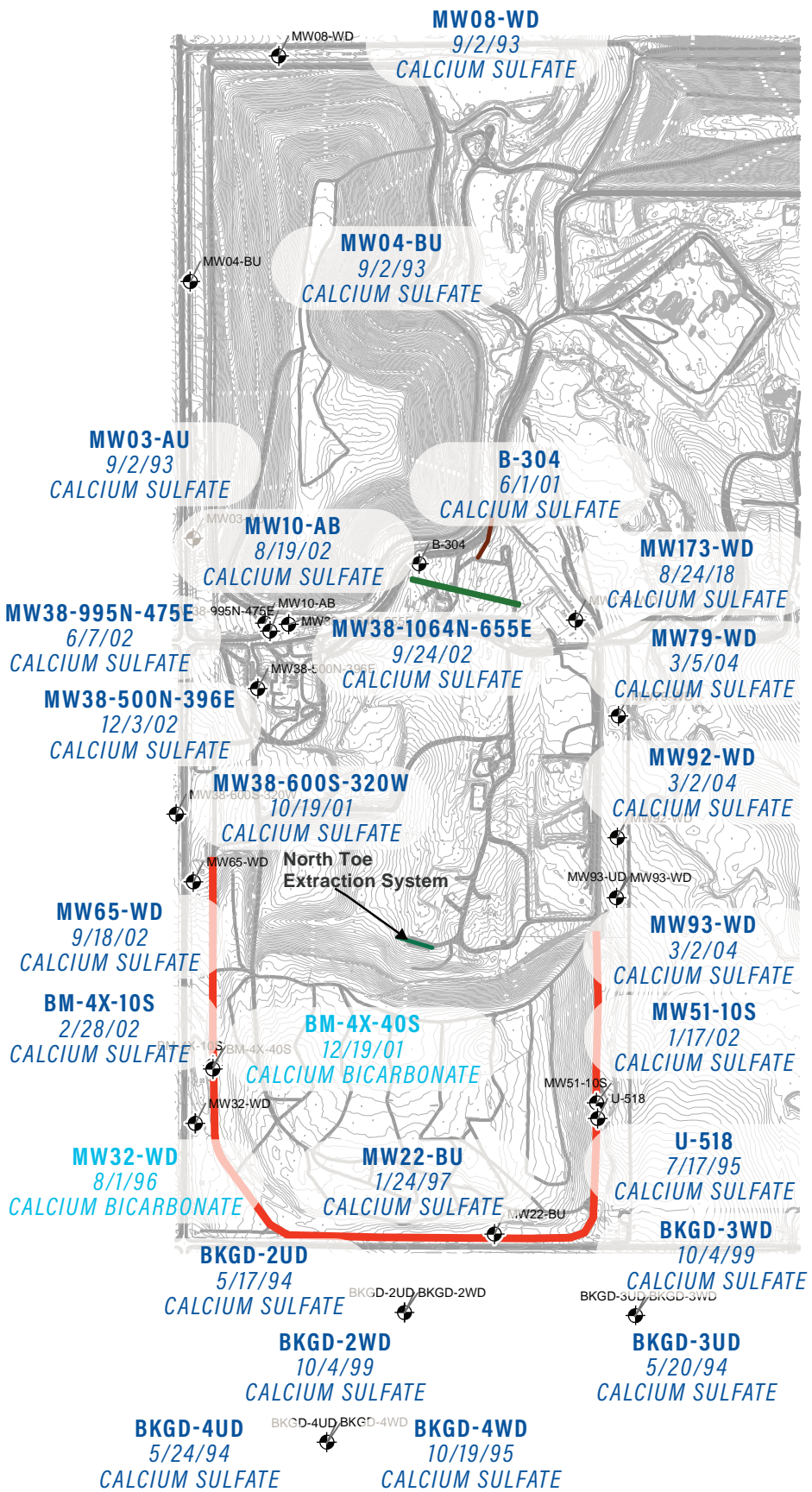
# 4-7 Weathering Progression



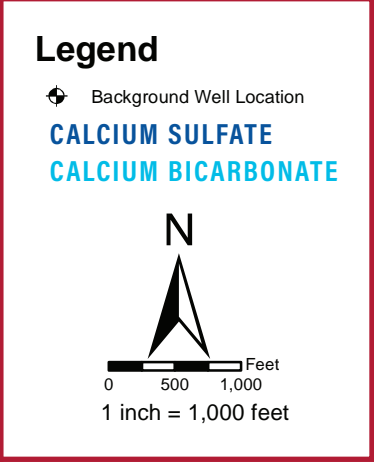
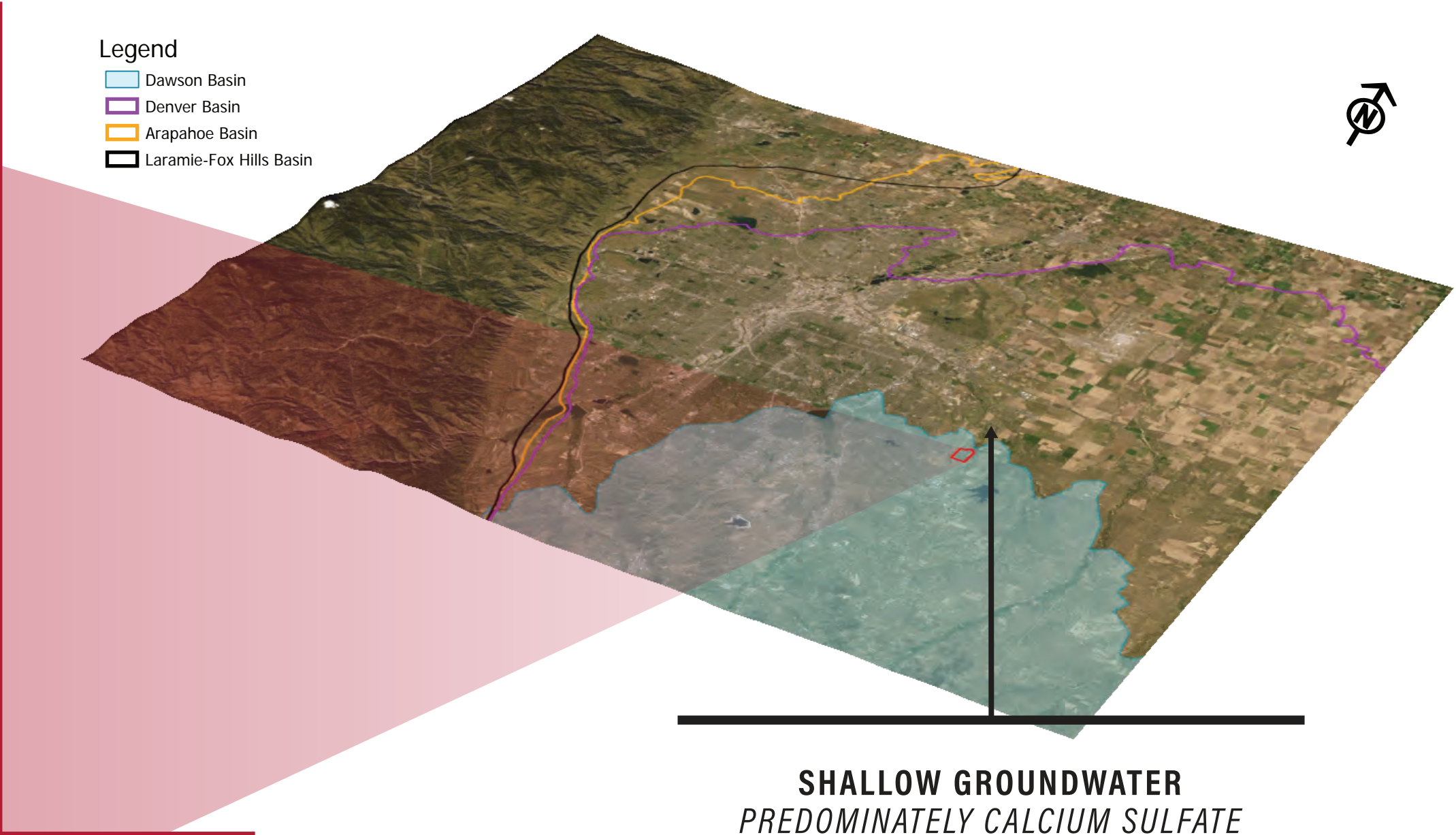


# 4-8 Groundwater Piper Type

*In Shallow, Deep, and Water Supply Wells*



- Legend
- Dawson Basin
  - Denver Basin
  - Arapahoe Basin
  - Laramie-Fox Hills Basin



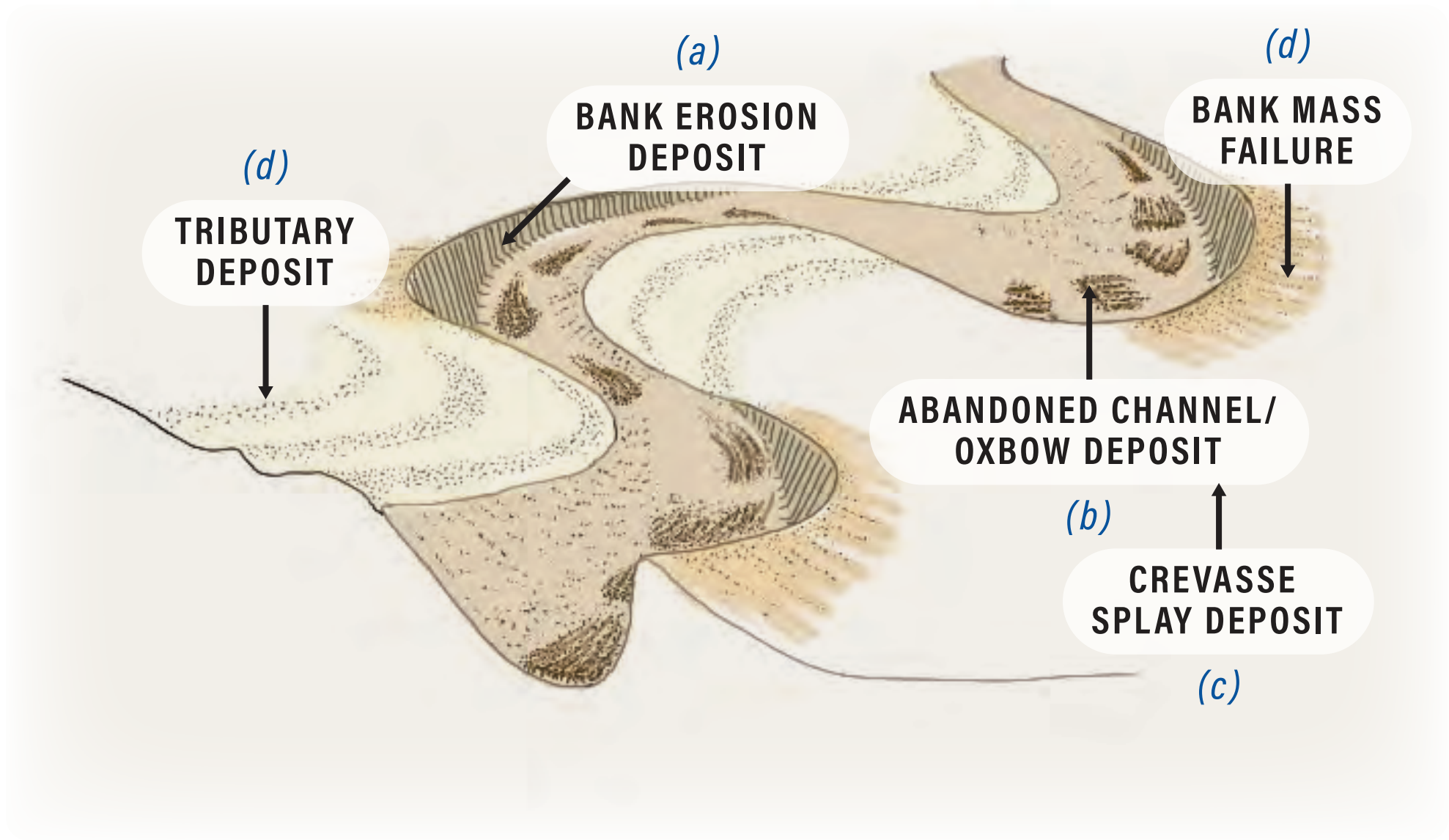
**SHALLOW GROUNDWATER**  
*PREDOMINATELY CALCIUM SULFATE*

**DEEP GROUNDWATER**  
*PREDOMINATELY SODIUM CHLORIDE*

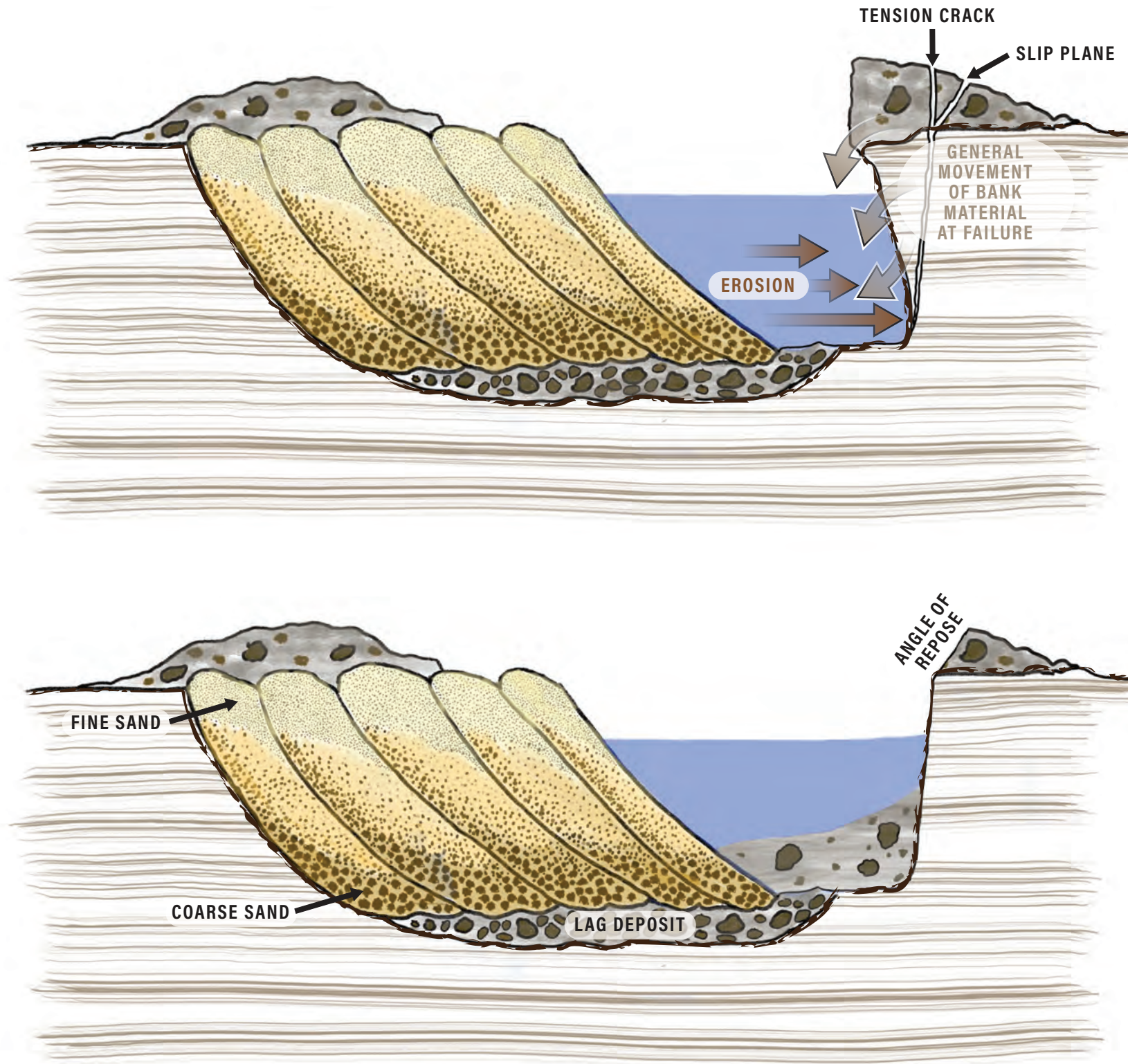
**DEEPER WATER SUPPLY WELLS (PRIVATE WELLS)**  
*SODIUM BICARBONATE*



# 4-9 Horizontal and Vertical Discontinuities



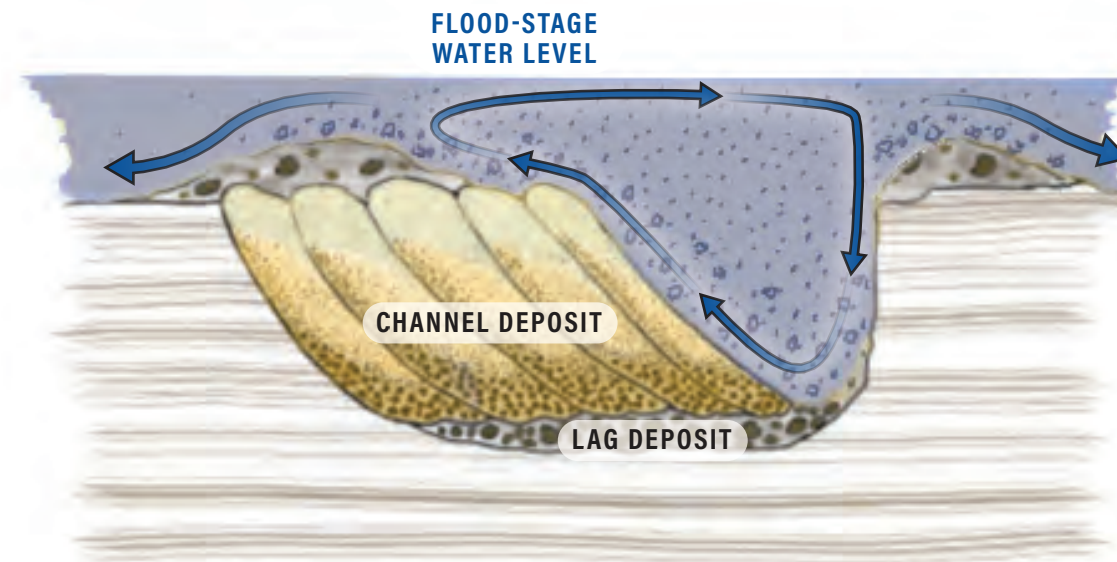
## 4-9 (a) Erosion Bank Deposit



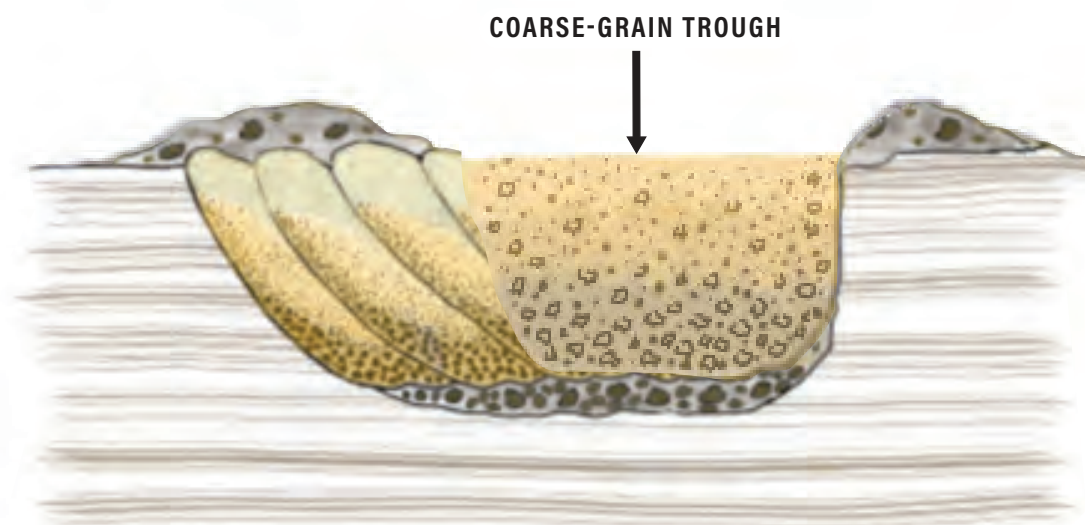


## 4-9 (b) Abandoned Channel / Oxbow Deposit

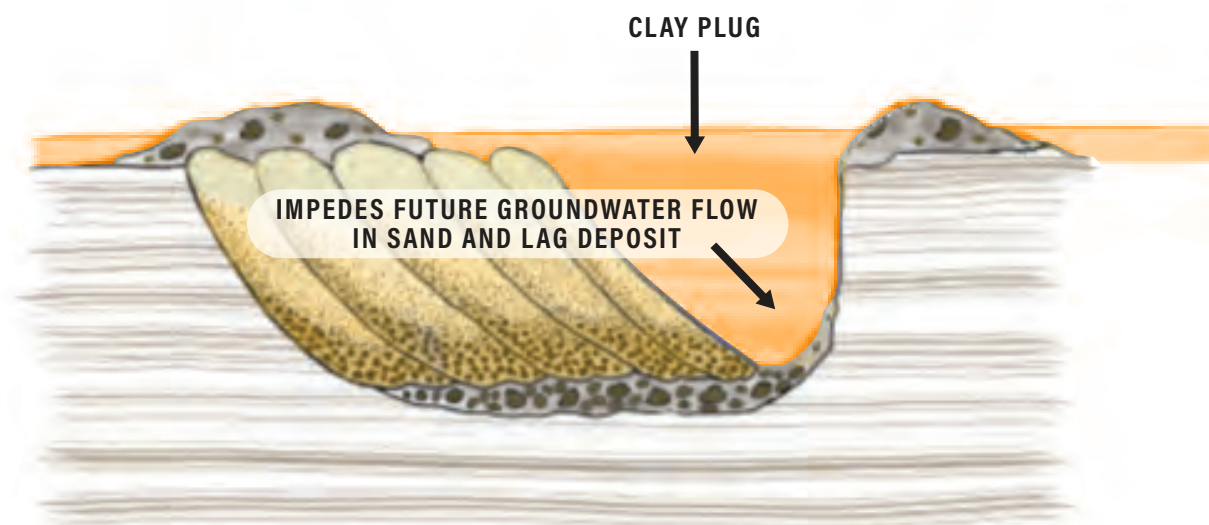
*Channel Profile Available for Deposition/Fill*



*High Velocity Flow /  
High Sediment Load*

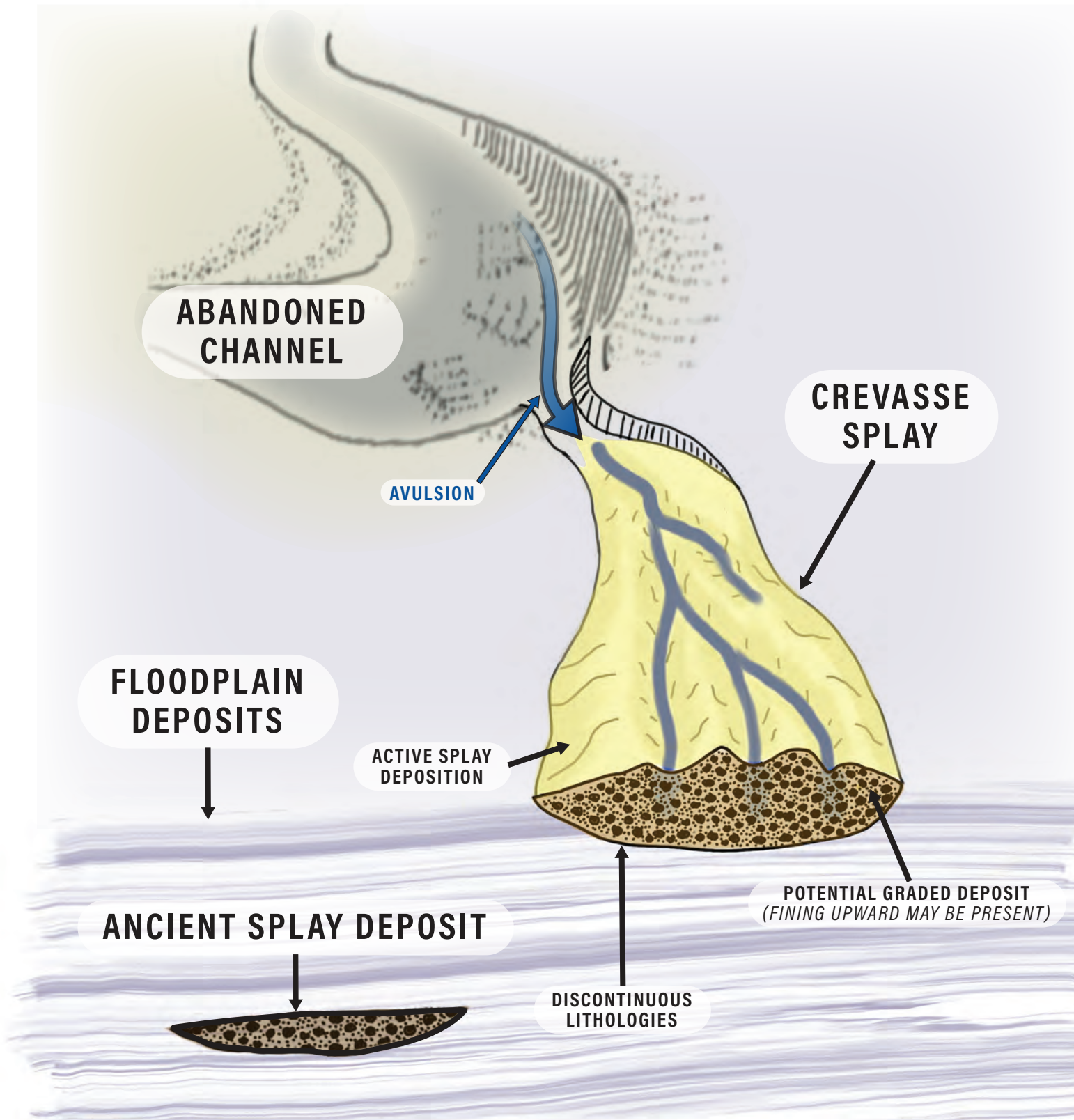


*Low Velocity Flow /  
Low Sediment Load*

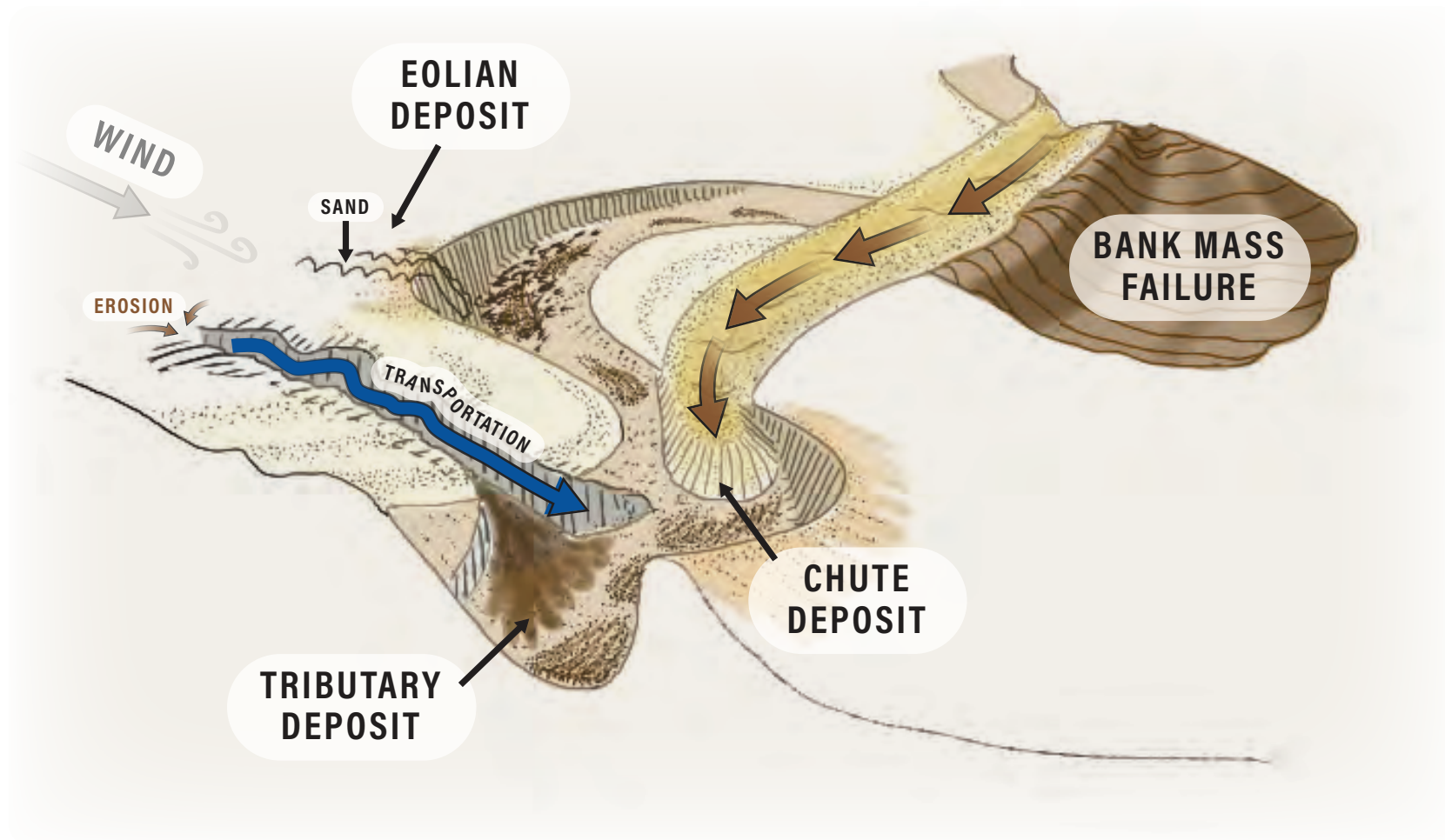




## 4-9 (c) Crevasse Splay Deposit



## 4-9 (d) Chute, Tributary, and Eolian Deposits





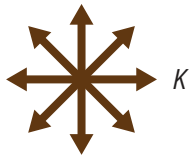
# 4-10 Stream Avulsion

1965 Aerial Photographic

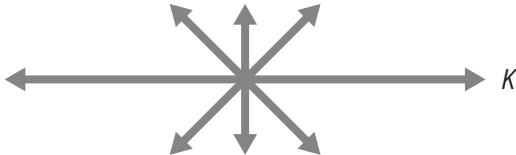




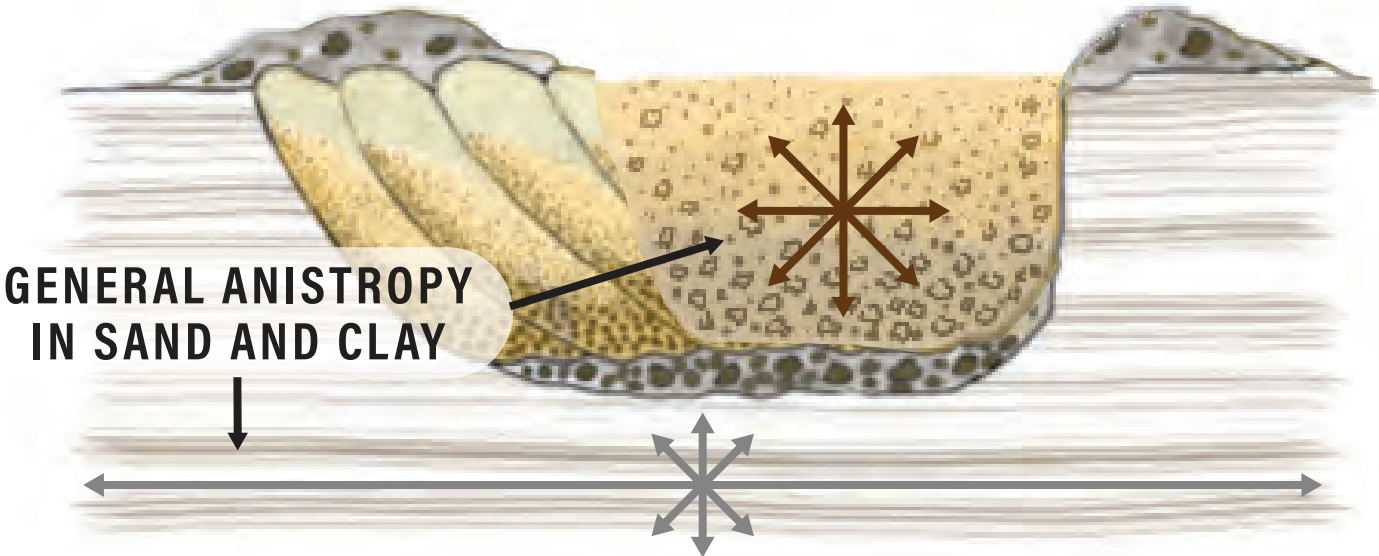
# 4-11 Anisotropy in Clay and Sand



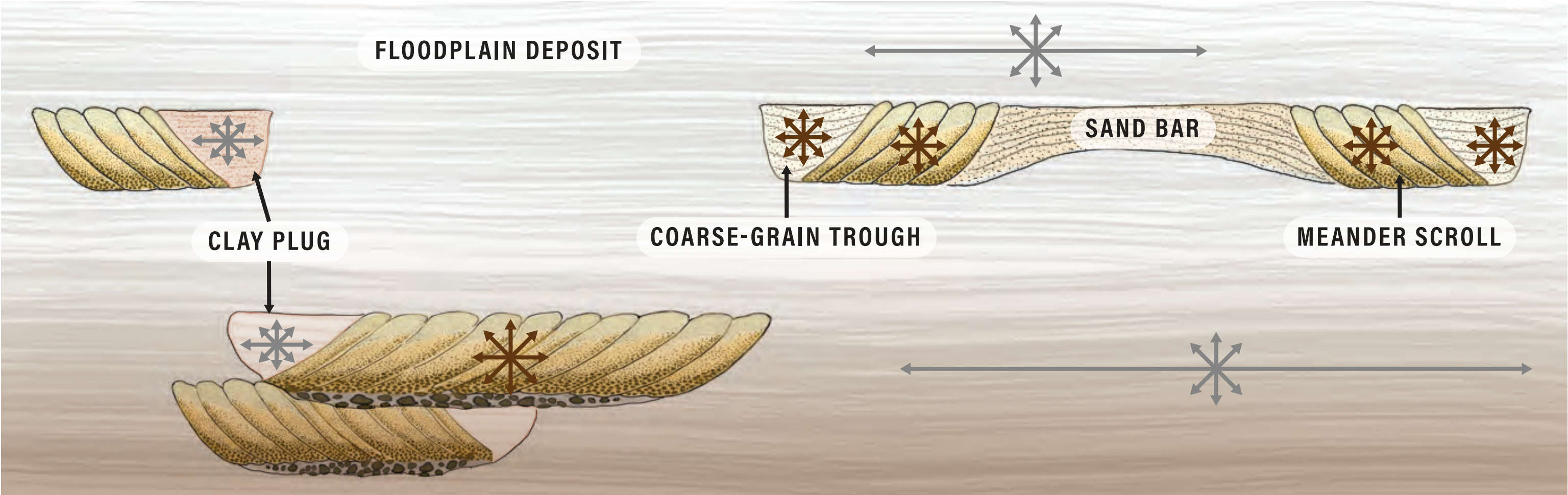
GRAIN SHAPE AND ORIENTATION  
CAN AFFECT ISOTROPY OR ANISTROPY



## Cross Sectional View



## Longitudinal View

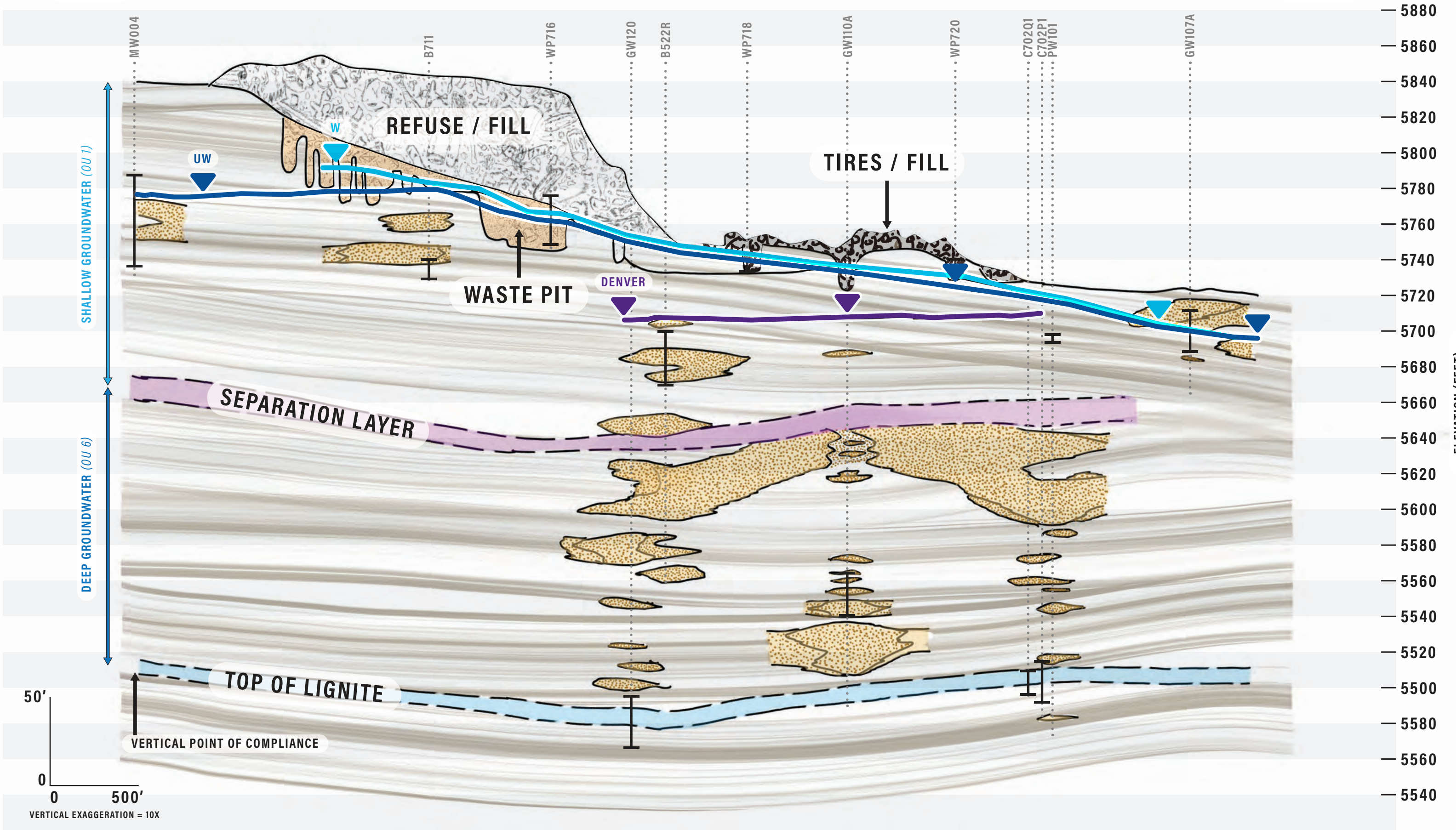




# 4-12 Separation Layer and Top of Lignite

← SOUTH

NORTH →





## 5.0 Remedy Components

The site's long-term remedy uses containment, collection, treatment, and monitoring to address contamination. Remedy components include a slurry wall, landfill cover, NTES, MW38, NBBW, SWRA, landfill gas removal, removal of waste pits, long-term monitoring, and on-site and off-site ICs. Under the selected sitewide remedy, landfill mass solids and soils are addressed through containment. Contaminated seepage and surface water are addressed through a drainage and underground collection system in the unnamed creek as part of the SWRA. Contaminated groundwater is addressed through containment, collection, and treatment by the on-site WTP. Landfill gas is addressed through containment, collection, and treatment, initially using enclosed flare technology but later through conversion to useable energy as part of a landfill GTEP. The response action identified for the FTPA addressed principal threats (drums, drum contents, and contaminated soils) through treatment and off-site disposal. However, due to safety concerns identified during implementation of the FTPA waste removal, the remedy was changed as described in Section 5.3. The remedy components are shown on Figure 3-3 and described in this section. All remedy components have received EPA certification of Remedial Action Completion or Construction Completion. The site's remedy is currently in the long-term O&M stage.

The operation, maintenance, and monitoring of the remedy components is conducted by the WSDs and documented in the semiannual SSRs. The SSRs document any remedial actions conducted during the reporting period; O&M activities associated with the remedy components; storage, treatment, and disposal of O&M and sampling waste; and sample collection and remedy monitoring. These activities are conducted in accordance with the site O&M plans (EMSI 2008, 2015, 2016, 2019a). The SSRs include updated databases containing site data and a summary of remedy effectiveness and compliance.

Groundwater monitoring is conducted by the WSDs in accordance with the GWMP (EMSI and Parsons 2018). The GWMP describes the specific data collection requirements, laboratory analysis, data evaluations, and decision rules that demonstrate the effectiveness of containment provided by four engineered components of the groundwater containment remedy (NBBW, NTES, perimeter slurry wall, and the MW38 gradient control contingency measure). The GWMP describes how changes (if detected) in water quality in deeper bedrock units beneath the interior of the site are evaluated for potential vertical migration of groundwater contamination. In addition, the GWMP includes the process for demonstrating compliance with groundwater performance standards along the downgradient portion of the POC. The POCs for the landfill gas remedy and the groundwater remedy at locations inside the site boundaries were established in the ROD (Figure 3-3). If the performance standards are not met during implementation or operation, the remedy requires implementation of appropriate contingency measures. The original performance standards listed in the ROD have been updated through subsequent documents. The current sitewide groundwater performance standards (as updated in 2018) are listed on Table 5-1. The results of the groundwater monitoring are presented in the SSRs.

### 5.1 North Boundary Barrier Wall

The NBBW is composed of a subsurface barrier wall, a collection drain and sump, three injection wells, and an injection trench located approximately 340 feet downgradient (north) of the wall. The NBBW is located immediately north of the Section 6/Section 31 section line at East Hampden Avenue (Figure 3-3). The purpose of the NBBW system is to contain and collect contaminated groundwater present in the alluvium and weathered Dawson and thereby prevent further migration beyond the northern boundary



of the site (EMSI 2015). The barrier wall and drain were installed between 1983 and 1984 and the injection trench was installed in 1984 pursuant to an AOC with EPA (EPA 1984) as an interim measure prior to issuance of the ROD.

The NBBW consists of a 960-foot-long compacted clay barrier keyed at least one foot into unweathered claystone bedrock along its entire length, as shown in transverse profile (Figure 5-1) and longitudinal profile (Figure 5-2). The barrier has a minimum width of 13 feet at its base and a maximum width of approximately 22 feet at its top. The top of the clay barrier/collection drain system is at an elevation of 5,700 feet above mean sea level (amsl), which is approximately 5 to 10 feet bgs. The barrier extends vertically through the weathered Dawson Formation and into the unweathered Dawson. Figure 5-2, which illustrates the lateral and vertical extent of the NBBW in longitudinal profile view (looking North), shows an interpretation of the variation in the base of the weathered Dawson. The weathered/unweathered interface is shown as a blue line along the length of the wall in Figure 5-2. This figure indicates that the vertical extent of the barrier (dashed black line) varies along the length of the wall.

The collection drain is positioned immediately upgradient (south) of, and parallel to, the clay wall (Figure 5-1). The collection drain incorporates connection laterals and a centralized sump. Groundwater enters the collection drain and laterals, then flows via gravity to the sump. The collection drain consists of a graded gravel backfill with a 6-inch perforated, filter-wrapped, plastic drainpipe that is graded to the central sump. The sump, in turn, has a foot sump that extends approximately 5.5 feet below the central sump. The schematic shown on Figure 5-1 and written descriptions of the construction of the wall in previous reports indicate that the clay barrier extends approximately 2 feet underneath the base of the drain. Compacted fill is emplaced around and above the NBBW system to original ground surface. Extraction from the sump is performed to maintain a constant groundwater level in the sump near the low point of the drain.

Nine extraction wells were installed from 2002 through 2011 (Figure 5-3). These wells were installed as part of a contingency measure and are described in more detail in Section 5.12. The wells are operated in the NBBW area to augment extraction and groundwater containment.

From 1984 through early 2001, treated groundwater (although not specifically treated to remove 1,4-dioxane) was injected into the injection trench, which is north of the NBBW and aligned with the unnamed creek streambed (Figure 5-3) (Parsons 2002b). The injection trench is approximately 370 feet long and 3 feet wide. Its depth is 12 feet bgs at the south end and tapers to 8 feet bgs at the north end. The base of the trench penetrates approximately one foot into naturally occurring sand and gravel. The lower four feet of the trench are backfilled with select gravel filter drain rock and pea gravel, which envelops a 4-inch diameter perforated pipe along the length of the trench. The gravel is covered by at least 4 feet of soil.

Beginning in late 2001, the extracted groundwater was treated by the WTP and ultimately discharged to an off-site POTW. After 2001, only potable water was injected into the trench. The potable water was injected to augment water rights for extracted groundwater, aid in containment at the NBBW, and flush residual contamination from the soil north of the NBBW for capture by extraction wells. In 2010, three 4-inch diameter injection wells (NBBW-IW-1, IW-2, and IW-3), screened in the weathered Dawson, were installed and initially used in conjunction with the injection trench to inject potable water. The three injection wells are positioned south of the injection trench along a line parallel to the NBBW as shown

on Figure 5-3. All injection into the injection trench ceased January 20, 2011, and potable water was injected only into the three injection wells. The injection of potable water was not a component of the remedy as described in the ROD, but EPA approved plans to implement injection in the three wells. Potable water injection ceased on October 2, 2018.

The effectiveness of the NBBW is evaluated as part of the compliance monitoring described in the GWMP (EMSI and Parsons 2018). In addition, the effectiveness of the NBBW is currently being evaluated as described in the NBBW Containment System Evaluation (CSE) Plan (EMSI 2020b), which includes the development of a numerical 3-dimensional finite-element groundwater simulation model (CDM Smith 2019). The NBBW CSE will include a detailed characterization of groundwater flow in the NBBW area, evaluate hydraulic containment at the NBBW, and identify future actions, if necessary, to contain contaminated groundwater.

## 5.2 Water Treatment Plant

The original WTP was constructed in 1984 to treat the contaminated groundwater captured by the NBBW using only GAC. In 1992, the WTP was upgraded to more efficiently remove the COCs (primarily VOCs) using a combination of air stripping and GAC. 1,4-dioxane was not a COC at the time. In accordance with the 1994 ROD, the original WTP was replaced with a new on-site WTP in 2000 to handle additional influent sources, treat 1,4-dioxane, and discharge treated effluent to an off-site POTW in accordance with the POTW's discharge permit. A BTS was added to the WTP in 2004 to treat additional waters containing 1,4-dioxane. The current WTP is divided into a main WTP and the BTS. EPA certified on August 11, 2005, that construction of the updated WTP was complete (EPA 2005a). The WTP was upgraded again in 2018/2019 to provide additional capacity. After the water is treated, it is piped off site into the municipal sewer system and then further treated by the Metro and Aurora's wastewater treatment facilities.

The WTP currently treats site waters from the NBBW (and associated extraction wells), NTES, east boundary extraction wells, MW38 extraction wells, on-site and off-site North End response action wells, LFG condensate, and miscellaneous sources such as purge water and potable water used for plant wash-down. These systems are described in more detail in the following sections.

The operation and maintenance of the WTP is conducted in accordance with the O&M manual (EMSI and Parsons 2019a). Compliance monitoring of plant effluent is required at three locations: MP-001, which is sampled for effluent quality; MP-002, which monitors effluent headspace air for explosive vapors; and MP-003, which monitors effluent flow rates and volumes. Early warning monitoring is conducted from five individual influent sources (Raw Water Storage Tanks, NBBW, MW38, North End on site and NTES, and LFG condensate water) and analyzed for VOCs and 1,4-dioxane. A sample is also collected from a composite of these sources for all other parameters (including radionuclides).

## 5.3 Former Tire Pile Area Remedy

During the 1970s and 1980s, 6 to 10 million tires accumulated at the Lowry Landfill. Most of the tires were placed on top of other waste that had been placed in three pits, each approximately 20 to 30 feet deep. Beginning in 1989, the tires were removed, shredded, and placed in an on-site monofill for future use as a fuel source. The three waste pits that lay under the tires collectively became known as the FTPA and were given special attention under the ROD because they contained accessible contaminated soil and waste liquids (Figure 3-3).

The original ROD called for materials in the FTPA to be excavated and transported off site for treatment and disposal, but EPA's modifications to the ROD in 1997 allowed for containment and treatment of these materials on site (EPA 1997). In 1998 and 1999, NAPL wastes were disposed of off-site as originally required by the ROD and surface and subsurface drums and contaminated soils within the middle FTPA waste pit were excavated and treated on site. A geomembrane-lined treatment cell was constructed adjacent to the middle waste pit. Soil and debris excavated from the middle waste pit were placed in the treatment cell, then covered with a second geomembrane. A system of slotted plastic pipes permitted vacuum extraction of soil gas from the treatment cell. This soil gas was thermally treated to destroy the VOCs recovered from the treatment cell. When the treatment cell contents were determined to be non-hazardous, the cell material, vent piping, and cover were hauled to and placed on top of the Section 6 landfill, then covered with a clay cap. In 2005, EPA approved the Final Interim Closeout Report for the middle waste pit remediation and construction of the treatment cell. The treatment cell completion report was approved by EPA in 2007 (EMSI 2007b).

During excavation of the middle waste pit, it was determined that additional emissions control measures would be needed for excavation of the other two FTPA pits (the north and south waste pits). In 1999, a portable enclosed structure was erected over the north waste pit to control vapor emissions during excavation, and a GAC system was used to treat the emissions prior to discharge of air from the enclosed structure. Shortly following commencement of excavation, the atmosphere inside the enclosed structure became too hazardous for continued operations and excavation ceased. EPA and the WSDs determined that further attempts to safely excavate waste from either the north or south waste pit in a manner that would be protective of workers and the public was not reasonably achievable. Alternatively, and with EPA's concurrence, and the WSDs pilot-tested in-situ thermal treatment of buried waste at the south waste pit. Results showed that only about half of the buried waste could be effectively treated or removed. Consequently, and with EPA's concurrence, the remedies for both the north and south waste pits were changed to NAPL removal via pumping, transport of extracted material to an off-site incineration facility, capping, and long-term monitoring. The north and south FTPA waste pits were covered with an earthen cover.

Following a period of public and official review, EPA formalized the alternate remedy through an amendment to the ROD (EPA 2005d). In 2010, EPA approved the Final Remedial Action Completion Report for the south waste pit (EMSI 2010). Remedial action at the north waste pit continued until 2013. EPA approved the Final Remedial Action Report for North Waste Pit and Former Tire Pile Area in 2013 (EMSI 2013).

O&M activities at the FTPA include maintenance of the existing cap on each waste pit and groundwater monitoring downgradient of the FTPA waste pits. These activities are documented in the SSRs.

#### 5.4 Landfill Cover

A 4-foot cover was installed over the main landfill unit after municipal solid waste disposal ceased in 1990; however, only a 2-foot interim soil cover was originally placed on the north face of the landfill mass so that landfilling could continue northward once the Superfund actions were concluded. Consequently, the ROD required an additional 2 feet of compacted clay cover over the north face of the landfill mass. The additional landfill cover was completed in 1999 and increased the total thickness of the north face cover to 4 feet, equal in thickness to the covers on other surface areas of the landfill mass. The extent of the landfill cover is shown on Figure 3-3.



The landfill cover was designed to reduce the potential for infiltration of rain and surface water into the landfill mass, prevent erosion, minimize the generation of leachate from contaminated fill material, better contain the landfill waste, and further reduce the potential for landfill gas release. Illustration 5-1 shows the landfill remedy components. The landfill cover includes a minimum of 4 feet of vegetated clay cover, with an ongoing maintenance program to promote positive drainage off the cover and prevent ponding on the cover. Reduction of infiltration into the landfill has reduced the volume of leachate impacting groundwater beneath the landfill. The landfill gas collection system is described in Section 5.9.

Long-term inspections, maintenance, and repairs of the landfill cover are ongoing in accordance with the O&M Manual for Covers and Stormwater (EMSI 2007a). The WSDs conduct a site-wide inspection annually and after significant snow/rain events. Inspections identify problems arising from settlement, cover or ditch erosion, sedimentation, and damage to security fences and gates, and repairs are made, as necessary. Weed control, mowing, and prairie dog mitigation is performed as necessary. Stormwater runoff is monitored annually during a precipitation event in accordance with the Stormwater Monitoring Plan (EMSI 2008). Runoff is analyzed at one location for oil and grease, pH, chemical oxygen demand, and total suspended solids. Landfill monitoring and repair activities are documented in the SSRs.

### 5.5 Surface Water Removal Action

The SWRA, constructed in 1992, prevents contaminated groundwater from contacting surface water within the unnamed creek streambed. In 1991, the City and County of Denver, WMC, and CWM entered into an AOC with EPA to construct and operate a SWRA that consisted of upgrading the existing groundwater WTP and constructing a collection system within the unnamed creek drainage to segregate contaminated groundwater from uncontaminated surface water. The SWRA extends between the NTES and the WTP access road (Figure 3-3). Final inspection of the SWRA was completed in January 1993 and EPA certified on August 11, 2005, that the SWRA was complete (EPA 2005a).

The SWRA consists of a permeable material (a blanket drain) placed beneath the streambed such that it contacted the top of groundwater as measured at the time of construction. The blanket drain was then covered with a minimum of 2-foot thick clay cover. The permeable material provides a pathway for groundwater to flow to the NBBW without contacting surface water. The top of the clay cover became the new thalweg for the unnamed surface drainage. A profile of the SWRA components is shown on Illustration 5-2. Under most conditions, the streambed is dry. During periods of surface runoff, when there is water in unnamed creek, the SWRA clay cover prevents contaminated groundwater from impacting uncontaminated surface water.

The SWRA is periodically monitored to ensure it is operating as designed. The results of the inspection and any necessary repairs are documented in the SSRs. Groundwater typically is encountered several feet below the SWRA and does not come into contact with either the SWRA liner or the blanket drain. For example, in the first half of 2017, the depth to groundwater beneath the SWRA was approximately 10 feet (EMSI and Parsons 2017).

### 5.6 Institutional Controls

As required by the 1994 ROD, on-site groundwater and land use is restricted by ICs, which include restrictive covenants, zoning, and district court water rights rulings. Within the site boundaries, land use is restricted to landfilling and monitoring or remediation activities. Water rights beneath the site are

owned by the City and County of Denver and restrictive covenants prevent drilling of new wells on site except for monitoring or remediation purposes. EPA and CDPHE have the authority to enforce these on-site land and groundwater use restrictions. The extent of the ICs is shown on Figure 5-4.

The land surrounding the site is owned by the City and County of Denver or the Lowry Environmental Protection/Cleanup Trust. The Trust is comprised of monies collected by Denver, WMC, and CWM in settlement of the third-party contribution actions against other potentially responsible parties at the site. Restrictive covenants run with the land to restrict land and groundwater use to landfilling, monitoring and remediation activities, industrial, commercial, utilities, agricultural, open space or recreational uses. In addition, an Aurora City Ordinance restricts the drilling, development, or use of wells within one-half mile of the boundaries of Section 6 if within the City (Aurora Code Section 138-154).

In accordance with the 2002 Institutional Control Plan (EPA 2002a), as amended in 2005 (Parsons 2005), the WSDs perform a well survey every five years for wells constructed within one half mile of the site. The most recent well survey was conducted in 2017. The 2017 well survey was extended five miles north of the site along the Murphy Creek drainage basin. The private and municipal wells located within the drainage basin are listed on Table 5-2. Figure 5-5 shows the locations of these wells, the search area north of the site and the approximate boundaries of the 1,4-dioxane plume (as of the first quarter 2017). Four wells are located within the footprint of the 1,4-dioxane plume and one well is located immediately adjacent to the plume. Two of these wells were identified as private domestic water supply wells and thus were sampled and analyzed for 1,4-dioxane. No 1,4-dioxane was detected in either well in 2017 or in any samples collected from the wells since sampling began in 2006 (EMSI 2020a).

## 5.7 Perimeter Slurry Wall

In February 1997, in accordance with the ROD, EPA and CDPHE approved a design for a subsurface slurry wall to be built around the east, west, and south sides of the site. Completed in December 1997, the wall is a continuous 8,800-foot subsurface clay/soil wall placed to deflect or limit inflow of clean groundwater to areas beneath the fill and to confine contaminated groundwater movement to the east, west, and south from waste pit sources within the landfill area (Figure 3-3). The slurry wall is approximately 3 feet wide and generally extends from a depth of 5 feet bgs to below the contact between the weathered and unweathered Dawson, at depths from 50 to 70 feet bgs. Illustration 5-3 is a profile of the perimeter slurry wall.

The effectiveness of the perimeter slurry wall is assessed by measuring the groundwater elevation in wells inside and outside of the wall to identify a potential hydraulic gradient (i.e., the potential direction of groundwater flow). If an outward hydraulic gradient is observed at a particular location along the wall (that is, the groundwater elevation is higher in the well inside the wall than in the well outside the wall), water quality data obtained from outside the wall are used to assess the effectiveness of the slurry wall at containing site contaminants. The decision rules for determining the effectiveness of containment by the slurry wall are described in the GWMP. The results of the assessment are documented in the O&M status reports (the SSRs) prepared semiannually by the WSDs.

A saturated sand layer beneath the wall near PM-4X/PM-4I appears to be hydraulically connected beneath the wall and for some distance parallel to the wall (EPA 2001b). The saturated sand layer is

approximately 2 feet thick beneath the wall. Observations of water levels in an exterior well during pumping of an interior well showed an almost immediate hydraulic response during pumping. These factors suggest significant hydraulic connection through or more likely beneath the wall. However, water level measurements indicate an inward hydraulic gradient across the slurry wall at this location, which prevents contaminant migration outside of the slurry wall.

Groundwater contamination has been detected at concentrations above the performance standards outside of the slurry wall, including the areas near wells PM-11X, PM15X, MW51-WD, and MW46-WD. Some areas of contamination were known to be present outside of the slurry wall at the time the wall was emplaced. Groundwater extraction wells were constructed in these areas as contingency measures, as required by the ROD. These extraction wells were placed where necessary to maintain inward gradients across the wall and address the areas of groundwater contamination outside the wall. The wall and extraction wells are intended to prevent contaminated water from escaping the site and to minimize the migration of groundwater from outside the wall flowing inward and contacting contaminated materials. The groundwater extraction wells around the slurry wall are described in Section 5.12.

The performance of the slurry wall was recently assessed and the wall's effectiveness in achieving slurry wall remedial action objectives was documented in the perimeter barrier wall effectiveness evaluation report (EMSI and Parsons 2021a).

### 5.8 North Toe Extraction System

The NTES was constructed in 1998 and is located at the northern edge of the former landfill area, near the center of the site (Figure 3-3). Full-time operation of the NTES did not begin until 2004 when the WTP was upgraded to include the BTS to treat the 1,4-dioxane. The NTES system was designed to intercept and collect groundwater within the alluvium and weathered Dawson formation that contains higher concentrations of site chemicals from the toe of the landfill beneath the unnamed creek drainage. The NTES consists of a 350-foot long permeable collection trench within the alluvium and weathered Dawson at the toe of the LLSS landfill. Unlike the NBBW, the NTES does not include a downgradient barrier wall. Groundwater is collected and extracted at two sump locations, which are operated to maintain a constant groundwater level in the sumps. Water collected at the sumps is transported via an underground double-walled pipeline to the on-site WTP. The NTES components are represented on Illustration 5-4(a) and (b). As shown on the illustration, the water levels upgradient of the NTES decrease to the groundwater level set point elevation in the NTES trench and extraction well(s).

The NTES sump system consists of two locations presently used for groundwater extraction: MPZ-10R and the NTES sump. MPZ-11 may also be used as an extraction point but has not been pumped recently. Trench water levels (as measured in MPZ-10R, NTES-180W, and MPZ-11) are maintained below the base of alluvium (elevation 5,740 feet amsl) (EMSI 2015).

If present, light non-aqueous phase liquid (LNAPL) is skimmed from the groundwater surface by timer-activated pneumatic pumps at the extraction points. If the thickness of the LNAPL exceeds 0.5 feet, extraction begins and continues until visual observation of the extracted LNAPL indicates the presence of water or until the LNAPL thickness is less than 0.5 feet. No LNAPL extraction has occurred since September 13, 2011.



The effectiveness of the NTES is demonstrated based on hydraulic monitoring. If the trench water levels remain below the base of the alluvium, the NTES is considered effective at capturing the contaminated groundwater emanating from the toe of the landfill. The performance of the NTES was recently assessed and the systems effectiveness in achieving remedy component specific measures of effectiveness was documented in the MW38, NTES, and North End Response Actions (NERA) effectiveness evaluation report (EMSI and Parsons 2021b).

### 5.9 Landfill Gas Collection and Treatment System

The Lowry gas collection system consists of 64 extraction wells within the landfill refuse area. The collection system was installed in 1996 (extraction wells EW-1 through EW-54) and 2006 (extraction wells EW-55 through EW-64). Illustration 5-1 shows the placement of the extraction wells within the landfill mass. Landfill gas treatment consists of a combination of an enclosed flare, candlestick flare, and a landfill GTEP. The GTEP began operation in 2008, and two additional candlestick flares were installed in 2010 (DADS Blower/Flare [DBF]) and 2015 (Flare Station 3 [FS3]). The WSDs conduct routine maintenance on the LFG collection system in accordance with the O&M manual (EMSI 2016) and monitor the LFG collection system in accordance with the Compliance Monitoring Plan for the LFG system (EMSI 2018).

LFG monitoring consists of collecting gas composition samples at the GTEP inlet, flare sampling locations DBF and FS3, and POC probes. The POC probes are outside the slurry wall to provide detection of any releases of LFG from the site. The locations of the monitoring probes are shown on Figure 5-6. The GTEP inlet and flare samples are analyzed for methane, carbon dioxide, oxygen and balance gas monitoring. POC probes are sampled biennially for COCs in soil gas and quarterly for methane. LFG sampling results are reported in the SSRs.

### 5.10 Wetlands Mitigation

Replacement wetlands were constructed northeast of the site to mitigate the loss of 0.87 acre of wetlands areas caused by SWRA construction activities within the unnamed creek. The wetland mitigation area is shown on Figure 3-3. Wetlands construction was completed in spring 1997, but heavy flooding in summer 1997 damaged the wetlands shortly after completion. The wetlands were reconstructed in fall 1998 and spring 1999. EPA certified on August 12, 2005, that all aspects of the wetlands mitigation work were fully performed (EPA 2005b).

### 5.11 Groundwater Monitoring Wells and Compliance/Effectiveness Program

A groundwater monitoring program has been implemented to verify that the site remedy remains effective and protective. Monitoring wells were installed to monitor for the potential migration of contaminants in groundwater beneath the site at concentrations in excess of performance standards. These wells are sampled regularly as part of the ongoing groundwater monitoring and compliance program conducted by the WSDs. EPA periodically collects split samples to confirm the results of the monitoring program – that is, EPA collects a duplicate sample at the same time as the WSDs, using the same methods and materials, and sends the split sample to a different laboratory for analysis. EPA certified on August 12, 2005, that construction of the performance and compliance monitoring remedy was complete (EPA 2005c). In addition, on September 24<sup>th</sup> and 26<sup>th</sup> 2005, EPA certified interim Remedial Action Completion of the groundwater monitoring program (EMSI 2007c). However, the wells and analytes included as part of the monitoring and compliance program have varied slightly over the years, as documented in the GWMP updates.

The WSDs conduct ongoing groundwater monitoring to demonstrate that the remedy achieves the RAOs. These data are collected to demonstrate (1) compliance with performance standards along the downgradient portion of the POC; (2) the effectiveness of the four engineered components of the groundwater containment remedy (perimeter slurry wall, NTES, NBBW, and MW38 extraction system); and (3) changes in water quality (if any) in deeper bedrock units beneath the interior of the site. The POC for vertical migration of groundwater is the Lignite Layer, as identified in the ROD.

The WSDs analyze the groundwater samples for the 29 chemicals. The chemicals are sampled and analyzed using the site-specific requirements and data validation methods presented in the GWMP and the most recent Lowry Landfill PQL study. The PQL study is updated annually, as required by the Consent Decree, to address performance standards (or permitted discharge limits for the WTP) that are less than the PQL of the analytical method. The PQL was last updated in December 2019 (EMSI 2019b).

### Compliance Monitoring

The compliance monitoring network consists of 60 monitoring wells completed at locations representative of areas where transport from the landfill would most likely occur in the following units:

- 26 alluvium/weathered Dawson monitoring wells,
- 16 unweathered Dawson monitoring wells,
- 6 upper Denver monitoring wells, and
- 12 lignite wells.

These 60 wells have been monitored for groundwater compliance since 2005. Most of these wells are located along the POC boundary except five interior wells. The locations and distribution of these wells are shown on Figure 5-7.

Groundwater performance standards have been established for chemicals in groundwater at the site (Table 5-1). Indicator chemicals applicable to compliance monitoring were selected to optimize the analyte list to ensure that the compliance monitoring focuses on chemicals that are most mobile, most likely to occur above performance standards, and are associated with the highest potential human health risks. The compliance monitoring analyte list was selected based on evaluation of the following criteria:

- (1) Identification of site-related chemicals previously detected in groundwater outside of the source area;
- (2) Screening of these chemicals to identify those for which performance standards have been established;
- (3) Identification of those chemicals that have previously been detected in groundwater outside of the source area at levels greater than half of their respective performance standards;
- (4) Screening of the chemicals identified in Step 3 to identify those with high potential for mobility; and
- (5) Screening of the chemicals remaining after Step 4 to identify those chemicals with a potential to occur at concentrations that pose a potential risk to human health.

These evaluations resulted in the identification of 29 chemicals to demonstrate compliance with performance standards. The analyte list for compliance sampling includes:

Arsenic	Bromoform
Cadmium	Carbon Tetrachloride
Nitrate	Chlorobenzene
Nitrite	Chloroform
1,1,1-Trichloroethane (1,1,1-TCA)	Cis-1,2-Dichloroethene
1,1,2,2-Tetrachloroethane	Dibromochloromethane
1,1,2-Trichloroethane	Ethylbenzene
1,1- DCA	Methylene Chloride
1,1-Dichloroethene	Naphthalene
1,2-DCA	PCE
1,2-Dichloropropane	Toluene
1,4-Dioxane	Trans-1,2-Dichloroethene
Acetone	TCE
Benzene	Vinyl Chloride
BDCM	

Compliance is assessed by comparing the long-term average concentration (90 percent upper confidence limit) for each COC at each location to the respective performance standard. Additional details on the procedures used to calculate the 90 percent upper confidence limit are provided in Appendix C of the GWMP (EMSI and Parsons 2018). The compliance evaluation includes a requirement for contingency measures in cases where performance standards are not met and there is a potential for off-site migration. The decision tree for performing compliance evaluations is illustrated on Figure 5-8.

#### Effectiveness Monitoring

Monitoring wells are used to evaluate the effectiveness of the remedy components, including the NTES, NBBW, and MW38 sand channel extraction systems. The specific design objectives vary for the containment features, but each feature provides hydraulic control that prevents downgradient transport of contaminants via groundwater flow (EMSI and Parsons 2018). The entire effectiveness monitoring network is shown on Figure 5-9. Individual effectiveness monitoring networks for the perimeter slurry wall, MW38 sand channel, and NBBW extraction systems are discussed in Section 5.12.

Indicator chemicals for the effectiveness evaluation of the NTES, NBBW, and MW38 sand channel extraction systems were not identified because the demonstration of effectiveness of these systems is based on hydraulic monitoring data. However, five compounds have been identified as indicator chemicals for demonstration of the effectiveness of the perimeter slurry wall: 1,1,1-TCA, 1,1-DCA, TCE, PCE, and 1,4-dioxane.



### Monitoring for Vertical Migration

The presence of a downward component to the hydraulic gradient at the site indicates that there is a potential for downward migration of contamination from the source area(s) into the underlying unweathered Dawson formation and then further into the upper Denver and lignite layers. The objective of monitoring for vertical migration is to monitor for potential vertical migration inside the POC beneath and immediately downgradient of the source area (EMSI and Parsons 2018). Monitoring for potential vertical migration is separate and distinct from compliance monitoring and monitoring performed to demonstrate the effectiveness of the various remedial components. The purpose of monitoring for potential vertical migration is to allow for ongoing assessment of the well network and sampling frequency used for the deeper compliance monitoring wells at the site. Water quality data obtained from the interior deeper monitoring wells is used to identify any modifications to the compliance monitoring well network and/or sampling frequencies for the deeper units, if any, that may be necessary to ensure detection of possible occurrences of contaminants above performance standards in the deeper units that may be migrating toward the horizontal or vertical POC (EMSI and Parsons 2018).

Vertical migration wells B-504A, B-712-LD, C-702P3, and GW-113 are sampled to assess the potential for vertical contaminant migration (Figure 5-9). Historically VOCs have been detected in unweathered Dawson wells B-712 and B712-UD at levels above performance standards. Therefore B-712-LD, screened in the unweathered Dawson, was included in the monitoring program to monitor potential vertical migration of contamination in the B-712 area, well B-712-LD is monitored to identify potential changes in water quality in the unweathered Dawson in this area. As only a limited number of upper Denver monitoring wells exist at the Site, additional water quality monitoring of the upper Denver is routinely performed to increase the overall reliability of the compliance monitoring network. Specifically, three upper Denver monitoring wells (GW-113, B-504A, and C-702P3) located internal to the Site are monitored to assess the water quality of the upper Denver.

These four wells (one unweathered Dawson and three upper Denver) are not located on the POC; therefore, water quality data from these wells is not used to assess compliance with groundwater performance standards and overall protectiveness of the remedy but to evaluate the effectiveness of the monitoring network (EMSI and Parsons 2018). Monitoring frequency is biennial for the unweathered Dawson well and every five years for the upper Denver wells.

### 5.12 Contingency Measures

The 1994 ROD included provisions for contingency measures if contaminant levels exceed performance standards at compliance boundaries during operation of the groundwater remedy. Contingency measures implemented at the LLSS include extraction wells installed at the perimeter slurry wall, the MW38 sand channel, and the NBBW. Extracted groundwater is sent to the WTP. The effectiveness of these contingency measures is monitored in accordance with the GWMP and reported semiannually in the SSRs.

**Perimeter Slurry Wall Extraction Wells.** The perimeter slurry wall effectiveness monitoring well network is used to determine if contingency measures are needed at the perimeter slurry wall (Figure 5-10). Contingency measures implemented at the slurry wall include extraction wells that were installed for gradient control or VOC removal outside of the wall. Air sparging systems have been installed in some

of the extraction wells to treat VOCs in groundwater. The air sparging systems operate intermittently to reduce concentrations of VOCs to below the performance standards.

Three extraction systems have been installed around the slurry wall (Figure 3-3):

- PM-11 – Groundwater extraction from two wells (PM-11I and BM-11I-100N) located on the interior of the slurry wall in the PM-11 area provide gradient control across the slurry wall.
- MW51-WD – Three wells located on the interior of the slurry wall provide gradient control (MW51I-WD-15N, MW51I-WD and MW51I-WD-35S). In addition, air sparging at MW70-WD (located outside the slurry wall) volatilizes the VOCs in groundwater.
- PM-15 – Six internal or northern wells provide gradient control. In addition, air sparging at BM-15N5 (located outside the slurry wall) volatilizes the VOCs in groundwater.

The development and continuation of an inward gradient at extraction well PM-15 is shown on Illustration 5-3. This illustration also depicts pre- and post-pumping groundwater levels along the perimeter slurry wall. The performance of the slurry wall was recently assessed and the walls effectiveness in achieving slurry wall remedial action objectives was documented in the perimeter barrier wall effectiveness evaluation report (EMSI and Parsons 2021a).

**MW38 Sand Channel Extraction Wells.** In 2002, two extraction wells were installed to pump contaminated groundwater from the MW38 sand channel, located north of the western portion of the slurry wall (Figure 3-3) (Parsons 2002a). EPA certified on August 11, 2005, that construction of the MW38 area gradient control contingency measures was complete (EPA 2005a). The effectiveness monitoring network for the MW38 sand channel is shown on Figure 5-11.

The MW38 channel is a natural feature which, due to the higher hydraulic conductivity of the channel sand deposits in this feature, results in convergent flow into the channel. The gradient control measure for the MW38 area was implemented in response to groundwater contamination that was detected in the weathered Dawson monitoring well MW38-WD prior to the first Five Year Report for the site. One of the extraction wells, MW38-170S-140W, is in the upgradient (south) portion of the MW38 sand channel while the other extraction well, MW38-1028N-256E, is in the downgradient (north) portion of the MW38 sand channel. Convergent flow into the channel has been enhanced by the groundwater extraction, creating an inward hydraulic gradient. Pumping initially was performed on a continuous basis but more recently occurs intermittently because the sand channel has been essentially dewatered. It takes several days for enough water to accumulate in the areas of the two wells to activate pumping (EMSI and Parsons 2017). A third well, MW38-825S-445E, is also pumped intermittently for source control.

MW38 channel and remedy components are shown in profile on Illustration 5-5. The illustration also depicts pre- and post-pumping groundwater elevations. As shown on the illustration, the post-pumping groundwater elevation is the lowest near extraction well MW38-1028N-256E at the northern portion of the channel, preventing or reducing groundwater migration north of the MW38 sand channel. Concentrations of 1,4-dioxane have decreased in wells MW38-1028N-256E and MW38-830N-230E since 2005. The performance of the MW38 extraction system was recently assessed and the systems effectiveness in achieving remedy component specific measures of effectiveness was documented in the Effectiveness Evaluation Report for MW38, NTES, and NERA (EMSI and Parsons 2021b).

**NBBW Extraction Wells.** Extraction wells augment groundwater extraction and containment at the NBBW. The locations of associated groundwater extraction wells are shown on Figure 5-3. The NBBW effectiveness monitoring network is shown on Figure 5-12. Groundwater is extracted from MW-113-EW-1, MW113-UD (unweathered Dawson), MW170-EW-1 and B-321. Extraction well MW114-WD is located north of MW113-EW-1, but it has not been actively pumped for several years. In addition, groundwater has been extracted from four wells located in a sand channel identified near MW77, near the LLSS site boundary on the northeastern side of the LLSS. These four extraction wells are MW77-EW-2, MW102-WD, MW77-EW-1, and MW98-WD. However, MW77-EW-2 has not been actively pumped for several years.

### 5.13 North End Response Actions

Before 2000, groundwater extracted from the NBBW area was treated with air stripping and GAC, which remove VOCs but did not treat 1,4-dioxane. The WTP has since been modified to include the BTS to treat 1,4-dioxane in the groundwater. In 2006 and 2007, a comprehensive sampling program was conducted downgradient of the NBBW, including off site to the north in Sections 31, 30, 24, and 19. The results of those investigations indicated that 1,4-dioxane occurs above its performance standard in both the NBBW area as well as in groundwater more than 2.5 miles downgradient (Figure 3-4).

North End response actions were implemented as a contingency measure on site and north of the site boundary in response to the discovery of 1,4-dioxane in this area. Extraction wells and associated collection piping in five extraction areas (Areas 1 through 5) were installed (Figure 5-13). The objectives of the response action were to reduce off-site migration of 1,4-dioxane, reduce the mass of 1,4-dioxane north of the site, and to ultimately bring compliance wells into compliance with groundwater performance standards. Extracted groundwater from all North End response action wells is introduced into the WTP, treated with on-site waters, and discharged to the POTW, in accordance with Metro Wastewater Discharge Permit No. 2360-6.

The WSDs completed a North End Investigation from 2018 to 2020, as recommended by the 2017 Five Year Review (EMSI and CDM Smith 2020b). The Five Year Review deferred the protectiveness determinations for OUs 1 and 6 and Sitewide until further information on the following issues and recommendations:

- (1) sampling and analyzing wells located within the footprint and immediately adjacent to the 1,4-dioxane plume north of the site,
- (2) developing an updated plume map and CSM to ensure there is not potential future exposure off-site to the North; based on the results, evaluate the need for a monitoring plan for wells located within the vicinity of the plume edge; and assessing the need for additional ICs for the 1,4-dioxane plume area, and
- (3) reviewing the vertical migration compliance well network and evaluating the need to install additional vertical compliance wells in the 1,4-dioxane plume area.

Two private domestic wells along East Jewell Avenue are sampled annually in the spring for 1,4-dioxane. The wells are screened in the Denver formation. The most recent sampling event was in June 2020. 1,4-dioxane has never been detected in either well above its method detection limit, which is always less than the performance standard of 0.9 µg/L. These sampling activities, inspection, and confirmation of abandonment of wells is documented in the Technical Memorandum Identification and Sampling of



Water Supply Wells Within and Immediately Adjacent to Off-Site 1,4-Dioxane Plume, completed June 3, 2020 (EMSI 2020a), and the Memorandum RE: Evaluation of Private Wells Identified as an Issue in the 2017 Five Year Review, rev June 1, 2020 (EMSI and the Tri-County Health Department [TCHD] 2020).

The North End Investigation Report includes an updated plume map and a conceptual model of the 1,4-dioxane plume along with a risk assessment. Seven additional monitoring wells were installed to evaluate potential vertical migration of contamination. A total of 12 shallow and deep groundwater monitoring wells were sampled and evaluated in the North End Investigation report. A number of wells sampled as part of the 2018 synoptic sampling event also were included in the North End Investigation. The groundwater samples were analyzed for 1,4-dioxane, VOCs, nitrate, and major anions and cations. Monitoring of wells within the North End study area is ongoing.

The North End Groundwater Monitoring Plan is being updated to include long-term monitoring of unweathered bedrock well MW179-UDEN (located on the Yale Avenue transect) semi-annually for 1,4-dioxane. The performance of the NERA was recently assessed and the systems effectiveness in achieving remedy component specific response action objectives was documented in the Effectiveness Evaluation Report for MW38, NTES, and NERA (EMSI and Parsons 2021b).

Table 5-1. Sitewide Groundwater Performance Standards									
Analyte	Performance Standard based on Minor Modification (dated 9/30/02) to ROD (dated 3/10/94)	Safe Drinking Water Act Maximum Contaminant Level (4th Five Year Review)	Colorado Basic Standard for Groundwater (effective 12/30/16)	Background	Reporting Limit	Performance Standard	Basis	Comments	Units
1,1,1-Trichloroethane	200	200	14,000 or 200 <sup>1</sup>		1	200	MCL <sup>2</sup>		ug/L <sup>3</sup>
1,1,2,2-Tetrachloroethane	0.055		0.18		1	1	Reporting Limit		ug/L
1,1,2-Trichloroethane	3	5	2.8-5 <sup>1</sup>		1	5	MCL		ug/L
1,1-Dichloroethane	990				1	990	noncarcinogenic risk-based		ug/L
1,1-Dichloroethene	7	7	7		1	7	MCL		ug/L
1,2,4,5-Tetrachlorobenzene	2		2.1		10	10	Reporting Limit		ug/L
1,2,4-Trichlorobenzene	70	70	70		4	70	MCL		ug/L
1,2-Dibromo-3-chloropropane	0.2	0.2	0.2		5	5	Reporting Limit		ug/L
1,2-Dibromoethane	0.05		0.018		1	1	Reporting Limit		ug/L
1,2-Dichlorobenzene	600	600	600		4	600	MCL		ug/L
1,2-Dichloroethane	0.4	5	0.38-5 <sup>1</sup>		1	5	MCL		ug/L
1,2-Dichloropropane	0.56	5	0.52-5 <sup>1</sup>		1	5	MCL		ug/L
1,2-Diphenylhydrazine	0.05		0.044		10	10	Reporting Limit		ug/L
1,3-Dichlorobenzene	620		94		10	94	CO GW Std <sup>4</sup>		ug/L
1,4-Dichlorobenzene	75	75	75		4	75	MCL		ug/L
1,4-Dioxane	8		0.35		0.9	0.9	PQL <sup>5</sup>		ug/L
2,3,7,8-Tetrachlorodibenzodioxin	0.00000022	0.00003	0.00000022 to 0.00003 <sup>1</sup>		0.00001	0.00003	MCL		ug/L
2,4,5-TP	50	50	50		1	50	MCL		ug/L
2,4,6-Trichlorophenol	2		3.2		10	10	Reporting Limit		ug/L
2,4-D	70	70	70		4	70	MCL		ug/L
2,4-Dichlorophenol	21		21		10	21	CO GW Std		ug/L
2,4-Dinitrophenol	14		14		30	30	Reporting Limit		ug/L
2-Butanone (MEK)	1904				6	1904	non-carcinogenic risk based		ug/L
2-Chlorophenol	0.1		35		10	35	CO GW Std		ug/L
2-Hexanone					5				ug/L
2-Methylnaphthalene	0.0031				4	10	Reporting Limit		ug/L
4,4'-DDE	0.1		0.1		0.05	0.1	CO GW Std		ug/L
4,4'-Dichlorodiphenyltrichloroethane (DDT)	0.1		0.1		0.05	0.1	CO GW Std		ug/L
4-Methyl-2-pentanone (MIBK)	158				5	158	non-carcinogenic risk based		ug/L
Acetone	1600				10	1600			ug/L
Alachlor	2	2	2		0.2	2	MCL		ug/L
Aldicarb	3		7		0.4	7	CO GW Std		ug/L
Aldicarb Sulfone	2		7		0.08	7	CO GW Std		ug/L
Aldicarb Sulfoxide	4		7		0.4	7	CO GW Std		ug/L
Aldrin	0.002		0.0021		0.05	0.05	Reporting Limit		ug/L
Alpha - BHC	0.006		0.0056		0.05	0.05	Reporting Limit		ug/L
Alpha, Gross	15		15	55.4		55.4	Background		pCi/L <sup>10</sup>
Aluminum	5000	200 (2°DW <sup>6</sup> )	5000	1950	100	5000	CO Agri. Std <sup>7</sup>		ug/L
Americium-241	0.46		0.15			0.15	CO GW Std		pCi/L
Antimony	6	6	6	770	20	770	Background		ug/L

Table 5-1. Sitewide Groundwater Performance Standards (Continued)									
Analyte	Performance Standard based on Minor Modification (dated 9/30/02) to ROD (dated 3/10/94)	Safe Drinking Water Act Maximum Contaminant Level (4th Five Year Review)	Colorado Basic Standard for Groundwater (effective 12/30/16)	Background	Reporting Limit	Performance Standard	Basis	Comments	Units
Aroclor 1260	0.005	0.5	0.175-0.5 <sup>1</sup>		1	1	Reporting Limit		ug/L
Arsenic	50	10	10	52.18	15	52.18	Background		ug/L
Asbestos (fibers/l)	30000	7000000	7000000			7000000	MCL	fibers/L, longer than 10um	
Atrazine	3	3	3		0.2	3	MCL		ug/L
Barium	1000	2000	2000	200	10	2000	MCL		ug/L
Benzene	5	5	5		1	5	MCL		ug/L
Benzidine	0.0002		0.00015		100	100	Reporting Limit		ug/L
Benzo(a)anthracene	0.1		0.0048-0.2 <sup>1</sup>		4	4	Reporting Limit		ug/L
Benzo(a)pyrene	0.01	0.2	0.0048-0.2 <sup>1</sup>		4	4	Reporting Limit		ug/L
Benzyl alcohol					10				ug/L
Beryllium	4	4	4	2.89	1	4	MCL		ug/L
Beta, Gross	80	80		67		80	MCL	4 millirems converted to pCi/L using Site conditions	pCi/L
Bis(2-Chloroethyl)Ether	0.03		0.032		10	10	Reporting Limit		ug/L
Bis(2-ethylhexyl)adipate	400	400	400		1.5	400	MCL	TIC <sup>8</sup>	ug/L
bis(2-Ethylhexyl)phthalate	4.8	6	2.5-6 <sup>1</sup>		10	10	Reporting Limit		ug/L
Boron	750		750	200	100	750	CO Agri Std		ug/L
Bromodichloromethane	0.3		0.56		1	1	Reporting Limit	80 for THMs <sup>9</sup>	ug/L
Bromoform	4		4		1	4	CO GW Std		ug/L
Cadmium	5	5	5	5.48	5	5.48	Background		ug/L
Carbazole					4				ug/L
Carbofuran	36	40	35-40 <sup>1</sup>		0.008	40	MCL		ug/L
Carbon Tetrachloride	0.3	5	0.5-5 <sup>1</sup>		1	5	MCL		ug/L
Cesium-134	80		80			80	CO GW Std		pCi/L
Chlordane	0.03	2	0.1-2 <sup>1</sup>		0.5	2	MCL		ug/L
Chloride	250000	250000 (2°DW)	250000	1000000	3000	1000000	Background		ug/L
Chlorobenzene	100	100	100		1	100	MCL		ug/L
Chloroethane					2				ug/L
Chloroform	6		3.5		1	3.5	CO GW Std	80 for THMs	ug/L
Chromium	50	100	100	11.04	10	100	MCL		ug/L
Chromium (hexavalent)	50			83.47	20	83.47	Background		ug/L
cis-1,2-Dichloroethene	70	70	14 - 70 <sup>1</sup>		1	70	MCL		ug/L
Cobalt	50		50 (Agri)	13.67	10	50	CO Agri Std		ug/L
Coliform (total)/ 100 ml	1	TT	2.2 (30 day avg.) 23 (maximum)			TT	CO GW Std	TT - treatment technique, >5% of samples test positive	org/100 ml
Color, color units	15	15 (2°DW)	15		5	15	CO GW Std		color units
Copper	200	1000 (2° DW) & 1300 (ACTION LEVEL)	200 (Agri)	90.9	15	200	CO Agri Std		ug/L
Corrosivity	non-corrosive	non-corrosive (2° DW)	non-corrosive		0.1	non-corrosive	CO GW Std	non-corrosive	ug/L
Cyanide	200	200	200	7.39	10	200	MCL	free cyanide	ug/L
Dalapon	200	200	200		2	200	MCL		ug/L
Di(2-ethylhexyl)adipate	400	400	400		1.5	400	MCL	TIC	ug/L
Dibenzofuran					4				ug/L



Table 5-1. Sitewide Groundwater Performance Standards (Continued)

Analyte	Performance Standard based on Minor Modification (dated 9/30/02) to ROD (dated 3/10/94)	Safe Drinking Water Act Maximum Contaminant Level (4th Five Year Review)	Colorado Basic Standard for Groundwater (effective 12/30/16)	Background	Reporting Limit	Performance Standard	Basis	Comments	Units
Dibromochloromethane	0.42		14		1	14	CO GW Std	80 for THMs	ug/L
Dieldrin	0.002		0.002		0.05	0.05	Reporting Limit		ug/L
Di-N-Octylphthalate					4				ug/L
Dinoseb	7	7	7		1	7	MCL		ug/L
Diquat	20	20	15-20 <sup>1</sup>		2	20	MCL		ug/L
Endothall	100	100	100		9	100	MCL		ug/L
Endrin	0.2	2	2		0.05	2	MCL		ug/L
Endrin Aldehyde	0.2		2.1		0.05	2.1	CO GW Std		ug/L
Ethylbenzene	680	700	700		1	700	MCL		ug/L
Fluoranthene	188		280		4	280	CO GW Std		ug/L
Fluoride	2000	4000	2000 (Agri)	50000	500	50000	Background		ug/L
Foaming Agents	500	500 (2°DW)	500 (DW)		200	500	CO DW Std		ug/L
Gamma - BHC	0.2	0.2	0.2		0.05	0.2	MCL		ug/L
Glyphosate	700	700	700		25	700	MCL		ug/L
Heptachlor	0.008	0.4	0.008-0.4 <sup>1</sup>		0.05	0.4	MCL		ug/L
Heptachlor Epoxide	0.004	0.2	0.004-0.2 <sup>1</sup>		0.05	0.2	MCL		ug/L
Hexachlorobenzene	1	1	0.022-1 <sup>1</sup>		10	10	Reporting Limit		ug/L
Hexachlorobutadiene	1		0.45		1	1	Reporting Limit		ug/L
Hexachlorocyclopentadiene	50	50	42-50 <sup>1</sup>		50	50	MCL		ug/L
Iron	300	300 (2° DW)	300 (DW)	2060.4	100	2060.4	Background		ug/L
Isophorone	40		140		10	140	CO GW Std		ug/L
Lead	15	15 (ACTION LEVEL)	50	50	9	50	CO GW Std		ug/L
Lead-210	0.037					0.037	carcinogenic risk		pCi/L
Malathion	2500		140		2	140	CO GW Std		ug/L
Manganese	50	50 (2° DW)	50 (DW)	1620	10	1620	Background		ug/L
Mercury	2	2	2	0.78	0.2	2	MCL		ug/L
Methoxychlor	40	40	35 - 40 <sup>1</sup>		0.1	40	MCL		ug/L
Methylene chloride	5	5	5.6 - 5 <sup>1</sup>		1	5	MCL		ug/L
Monohydric Phenol	1								
Naphthalene	6.2		140		1	140	CO GW Std		ug/L
Nickel	2		100	57.9	40	100	CO GW Std		ug/L
Nitrobenzene	3.5		14		10	14	CO GW Std		ug/L
Nitrogen, Nitrate	10000	10000	10000	28000	500	28000	Background		ug/L
Nitrogen, Nitrate plus Nitrite	10000		10000	34000	100	34000	Background		ug/L
Nitrogen, Nitrite	1000	1000	1000		500	1000	MCL		ug/L
Oxamyl	200	200	175-200 <sup>1</sup>		0.04	200	MCL		ug/L
Pentachlorobenzene	6		5.6		10	10	Reporting Limit		ug/L
Pentachlorophenol	1	1	0.088 - 1 <sup>1</sup>		50	50	Reporting Limit		ug/L
pH	6.5-8.5	6.5-8.5 (2° DW)	6.5 - 8.5 (DW)		0.1	6.5-8.5	CO DW Std		ug/L
Phenanthrene	0.0031				4	4	Reporting Limit		ug/L
Phenol	300		2100		10	2,100	CO GW Std		ug/L
Picloram	500	500	490		0.5	500	MCL		ug/L
Plutonium-238	0.15					0.15	CO GW Std		pCi/L
Plutonium-239	0.15		0.15			0.15	CO GW Std		pCi/L
Plutonium-239/240	0.15		0.15			0.15	CO GW Std		pCi/L

Table 5-1. Sitewide Groundwater Performance Standards (Continued)

Analyte	Performance Standard based on Minor Modification (dated 9/30/02) to ROD (dated 3/10/94)	Safe Drinking Water Act Maximum Contaminant Level (4th Five Year Review)	Colorado Basic Standard for Groundwater (effective 12/30/16)	Background	Reporting Limit	Performance Standard	Basis	Comments	Units
Plutonium-240	0.15		0.15			0.15	CO GW Std		pCi/L
Potassium-40	1.9					1.9	carcinogenic risk		pCi/L
Radium-226	5					5			pCi/L
Radium-226/228	5	5	5			5	MCL		pCi/L
Radium-228	5					5			pCi/L
Selenium	10	50	50	371.98	20	371.98	Background		ug/L
Silver	50	100 (2° DW)	50		10	50	CO GW Std		ug/L
Simazine	4	4	4		0.5	4	MCL		ug/L
Strontium-90	8		8			8	CO GW Std		pCi/L
Styrene	100	100	100		1	100	MCL		ug/L
Sulfate	250000	250000 (2° DW)	250000 (DW)	2400000	5000	2400000	Background		ug/L
Tetrachloroethene	5	5	17 - 5 <sup>1</sup>		1	5	MCL		ug/L
Thallium	2	2	2		15	15	Reporting Limit		ug/L
Thorium-228	0.16					0.16	carcinogenic risk		pCi/L
Thorium-230	60		60			60	CO GW Std		pCi/L
Thorium-232	60		60			60	CO GW Std		pCi/L
Toluene	1000	1000	560 - 1000 <sup>1</sup>		1	1000	MCL		ug/L
Toxaphene	0.03	3	0.032-3 <sup>1</sup>		2	3	MCL		ug/L
trans-1,2-Dichloroethene	100	100	140 - 100 <sup>1</sup>		0.5	100	MCL		ug/L
trans-1,3-Dichloropropene	87				3	87			ug/L
Trichloroethene	5	5	5		1	5	MCL		ug/L
Tritium	20000		20000			20000	CO GW Std		pCi/L
Uranium-234	30	30				30	MCL	Total U MCL	pCi/L
Uranium-235	30	30				30	MCL	Total U MCL	pCi/L
Uranium-238	30	30				30	MCL	Total U MCL	pCi/L
Vanadium	100		100	16.65	10	100	CO Agri Std		ug/L
Vinyl chloride	2	2	0.023-2 <sup>1</sup>		2	2	MCL		ug/L
Xylenes, Total	10000	10000	1400-10000 <sup>1</sup>		2	10000	MCL		ug/L
Zinc	2000	5000 (2° DW)	2000 (Agri)	403	20	2000	CO Agri Std		ug/L

Notes:

<sup>1</sup> Whenever a range of standards is listed and referenced to this footnote, the first number in the range is a strictly health-based value, based on the Commission's established methodology for human health-based standards. The second number in the range is a maximum contaminant level, established under the federal SDWA has been determined to be an acceptable level of this chemical in public water supplies, taking treatability and laboratory detection limits into account. The Commission intends that control requirements for this chemical be implemented to attain a level of ambient water quality that is at least equal to the first number in the range except as follows:

\* Where groundwater quality exceeds the first number in the range due to release of contaminants that occurred prior to September 14, 2004 (regardless of the date of discovery or subsequent migration of such contaminants), clean-up levels for the entire contaminant plume shall be no more restrictive than the second number in the range or the groundwater quality resulting from such a release, whichever is more protective.

\* Wherever the Commission has adopted alternative, site-specific standards for a chemical, the site-specific standards shall apply instead of the statewide standards.

For sites for which the clean-up standards have been established prior to September 14, 2004, the Commission does not intend the adoption of this range of standards to result in changes to the require cleanup, unless such change is mandated by the implementing agency's independent statutory authority.

<sup>2</sup> MCL - Maximum Contaminant Level

<sup>3</sup> ug/L - micrograms per liter

<sup>4</sup> CO GW Std - Colorado groundwater standard

<sup>5</sup> PQL - practical quantitation limit

<sup>6</sup> 2° DW - Secondary drinking water standard

<sup>7</sup> CO Agri Std - Colorado agricultural standard

<sup>8</sup> TIC - analyzed as a tentatively identified compound

<sup>9</sup> THM - total halomethanes

<sup>10</sup> pCi/L - picoCuries per liter

**Table 5-2. Private/Municipal Wells within the Murphy Creek Drainage**

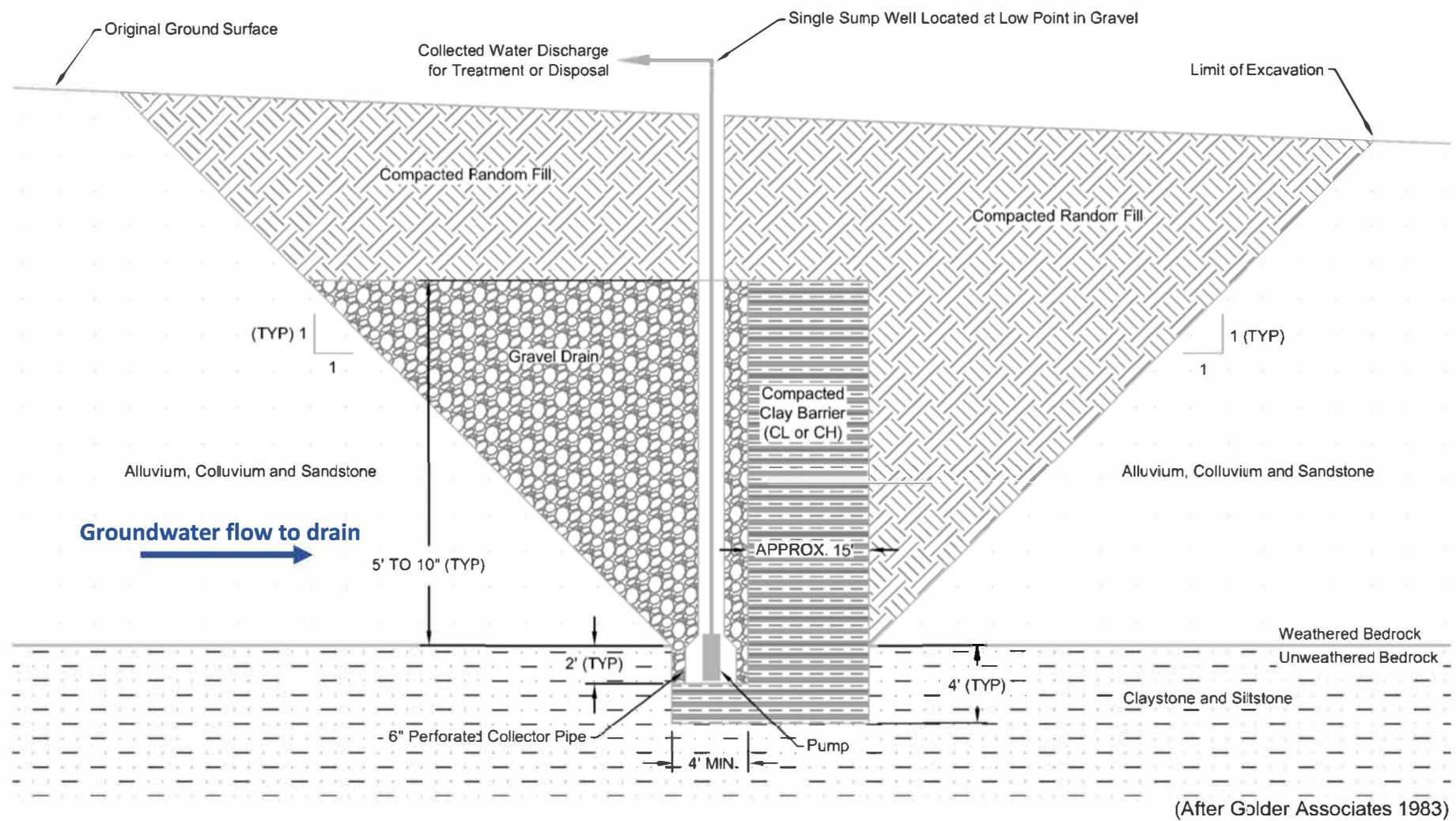
Identification Number	Use	Aquifer	Owner
1750	Domestic	Unspecified	Superior Sand and Gravel
1795	Domestic	Denver	Private Resident
1807	Domestic	Denver	Private Resident
1819	Domestic	Unspecified	Private Resident
1821	Other	Unspecified	City of Aurora
1867	Domestic	Unspecified	Private Resident
1879	Domestic	Unspecified	Private Resident
1889	Domestic	Unspecified	Private Resident
1890	Domestic	Unspecified	Private Resident
1940	Unspecified	Upper Arapahoe	St. Simeon Cemetery Associations
2000	Stock	Quaternary Alluvium	West Arapahoe Soil Conservation
2001	Stock	Denver	Private Resident
2009	Commercial	Arapahoe	East Creek Valley Water
2014	Commercial	Laramie Fox Hills	East Creek Valley Water
2027	Other	Quaternary Alluvium	City of Aurora
2082	Domestic	Denver	Private Resident
2084	Domestic	Denver	Private Resident
2085	Domestic	Denver	Private Resident
2273	Stock	Unspecified	Buckley Investment Camp
2344	Domestic	Denver	Private Resident
2448	Stock	Lower Dawson	Vincent Murphy Chev Co Inc.

**Notes:**

Wells listed were identified in the 2017 well survey (EMSI and Parsons 2017). This table does not include the wells owned by Waste Management or Lowry Environmental Protection/Cleanup Trust.

Engineering Management Support, Inc. (EMSI). 2017. Remedial Action and Operations & Maintenance Status Report: January Through June 2017, Lowry Landfill Superfund Site. For City and County of Denver, CWM, and WMC. September 30.





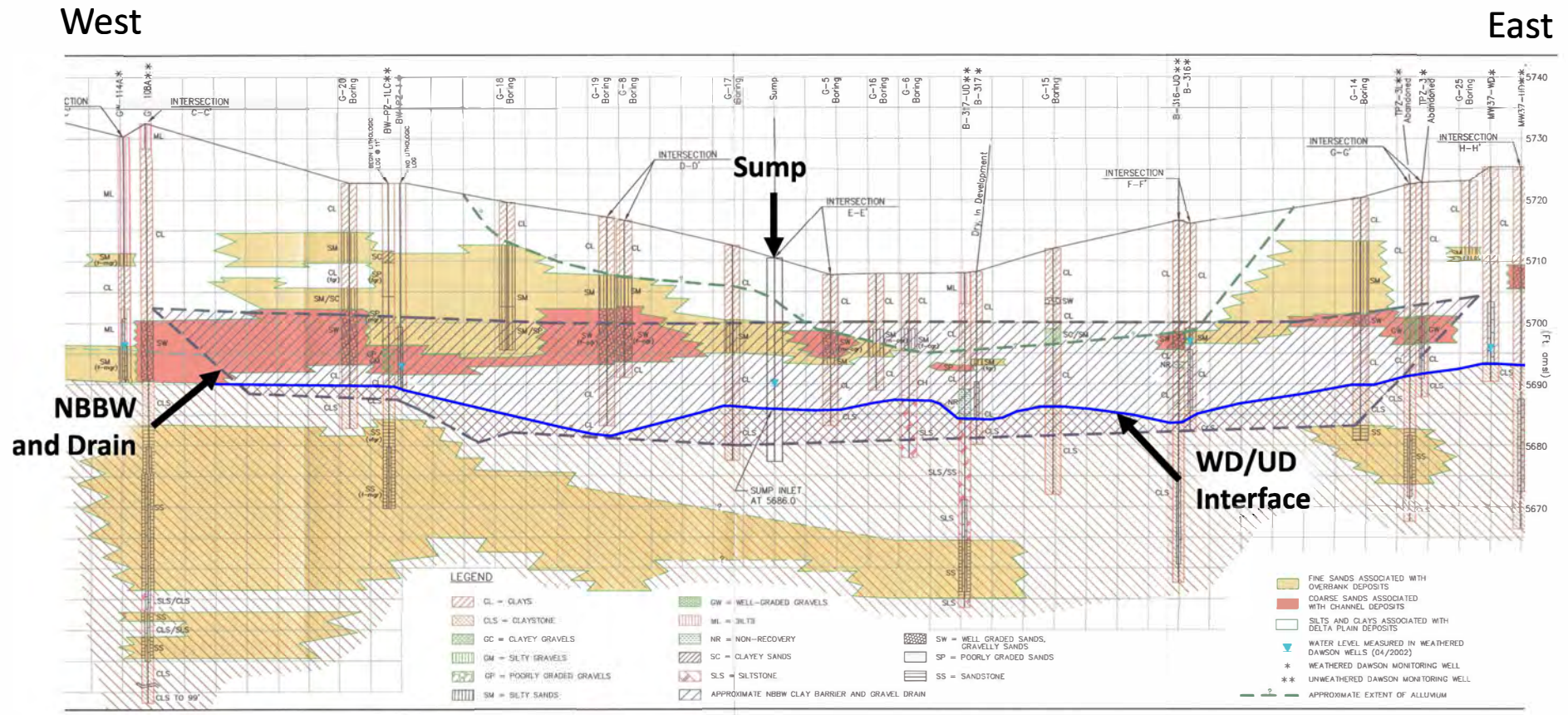
## LOWRY LANDFILL SUPERFUND SITE

Arapahoe County, Colorado

**Figure 5-1  
North Boundary Barrier Wall  
Transverse Profile**

# NBBW Longitudinal Profile

Base elevation of drain and barrier varies along the length of the NBBW



**LOWRY LANDFILL SUPERFUND SITE**  
 Arapahoe County, Colorado

**Figure 5-2**  
**North Boundary Barrier Wall**  
**Longitudinal Profile**

Source: Parsons



Hachures - indicating zone of depression created by extraction well

Injection Wells  
Operation suspended 10/2/18

Injection Trench  
Operation suspended 1/20/11

NBBW

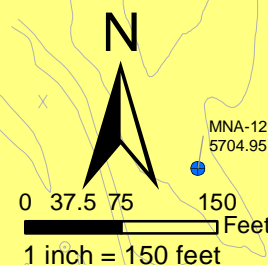
### Legend

- Water Elevation Contour (2-foot interval)  
(dashed where inferred)
- Injection Trench
- Groundwater Monitoring Well
- Compliance Wells highlighted with blue
- Groundwater Extraction Well
- Groundwater injection Well
- Groundwater Flow Direction
- Zone of Containment caused by NBBW  
and Response Action Pumping
- NBBW
- Area where the WD is dry

Note: The water elevation value  
for the fully penetrating well when twinned  
by a partially penetrating piezometer  
was honored for contouring

Dry - Water Level Below Base of Screen

Groundwater elevations  
- 4th Quarter 2019



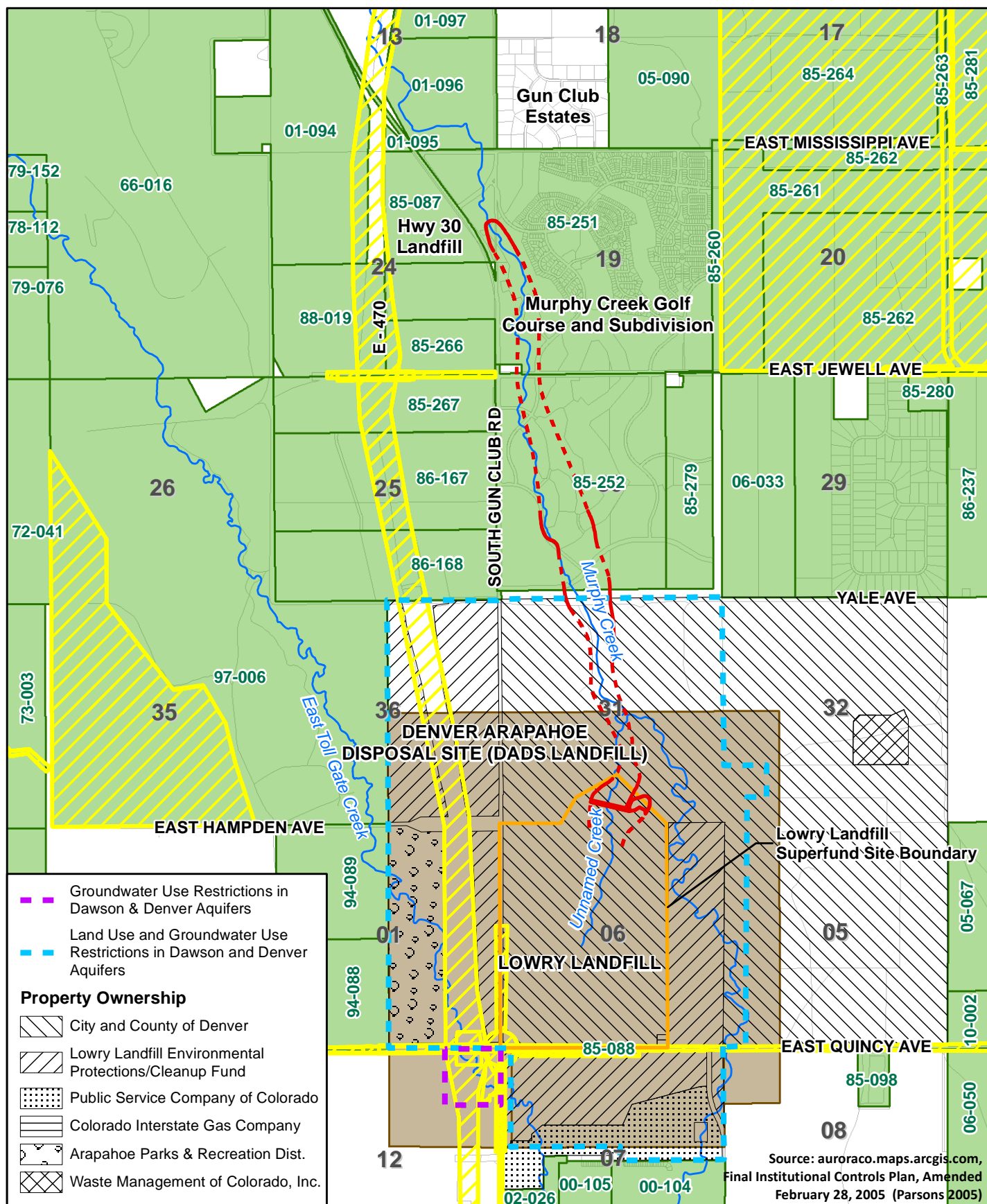
### LOWRY LANDFILL SUPERFUND SITE

Arapahoe County, Colorado

**Figure 5-3**  
**North Boundary Barrier Wall Area**  
**and Components**

Source: Fig 4-14, October 2019  
(Parsons 2020)

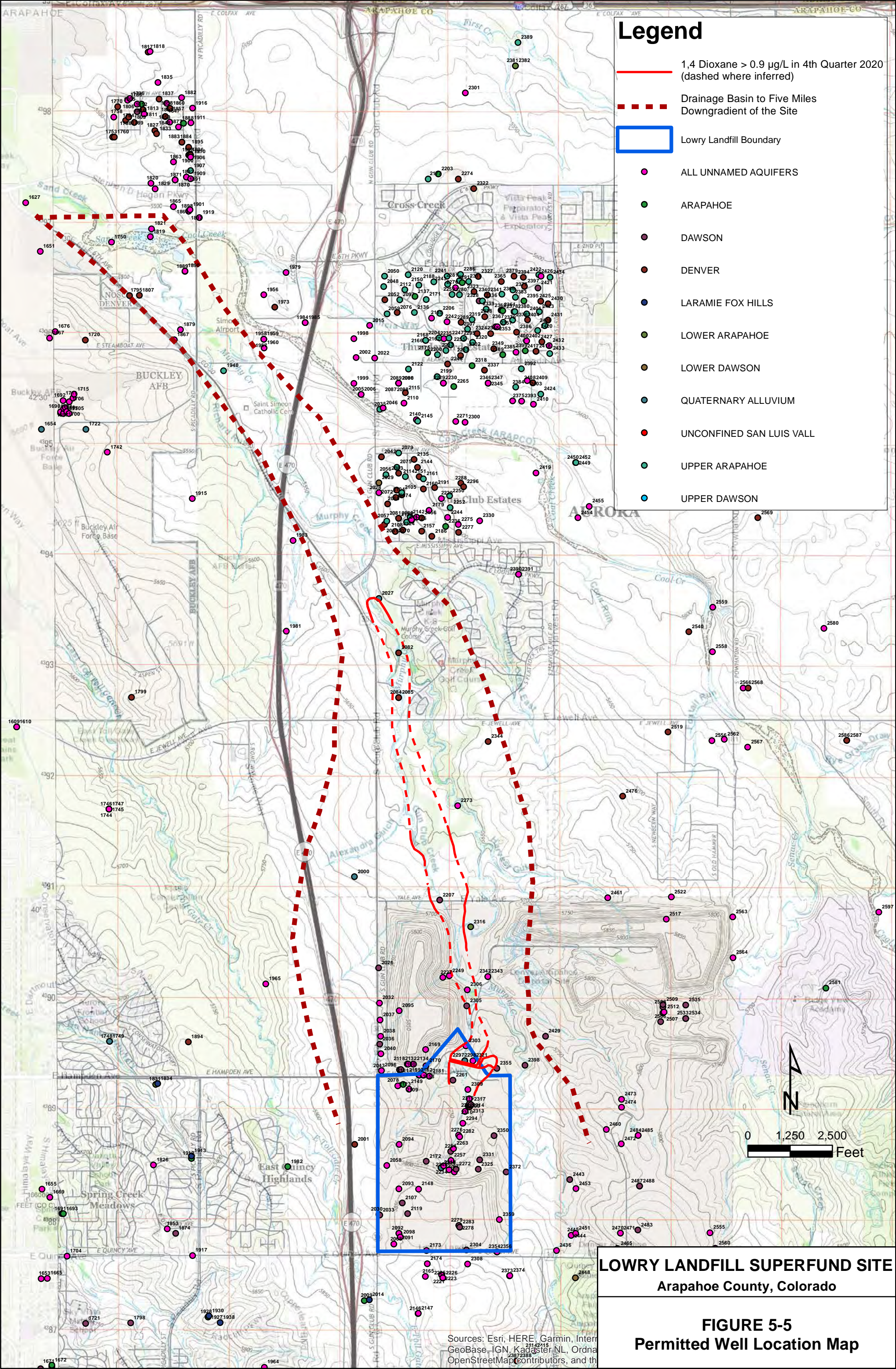




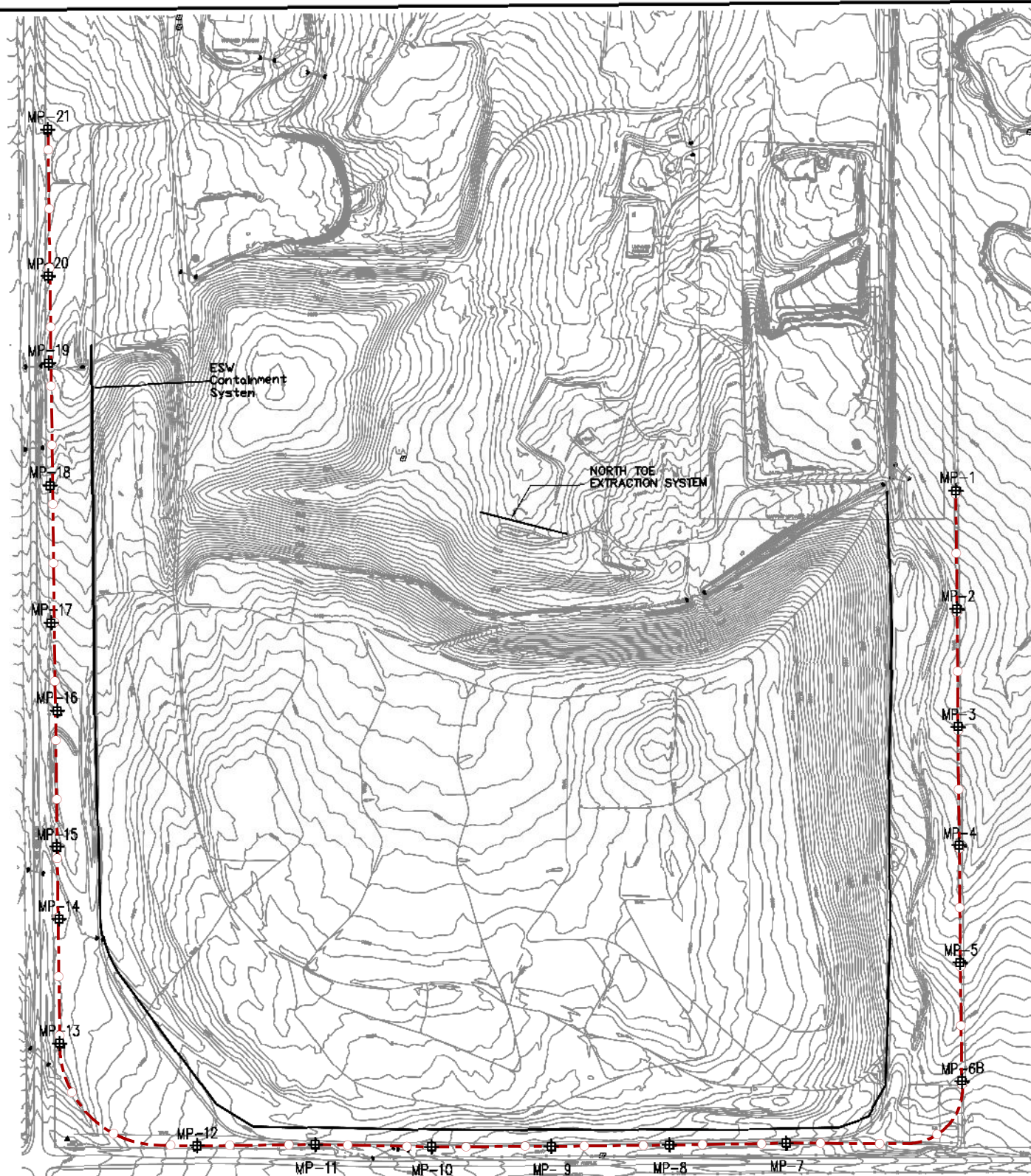
## LOWRY LANDFILL SUPERFUND SITE Arapahoe County, Colorado

**Figure 5-4  
Extent of the Institutional Controls**



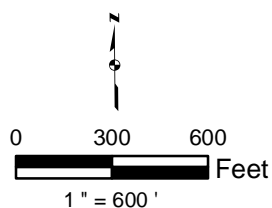






**LEGEND:**

- ⊕ LFG Monitoring Point
- --- LFG Compliance Boundary

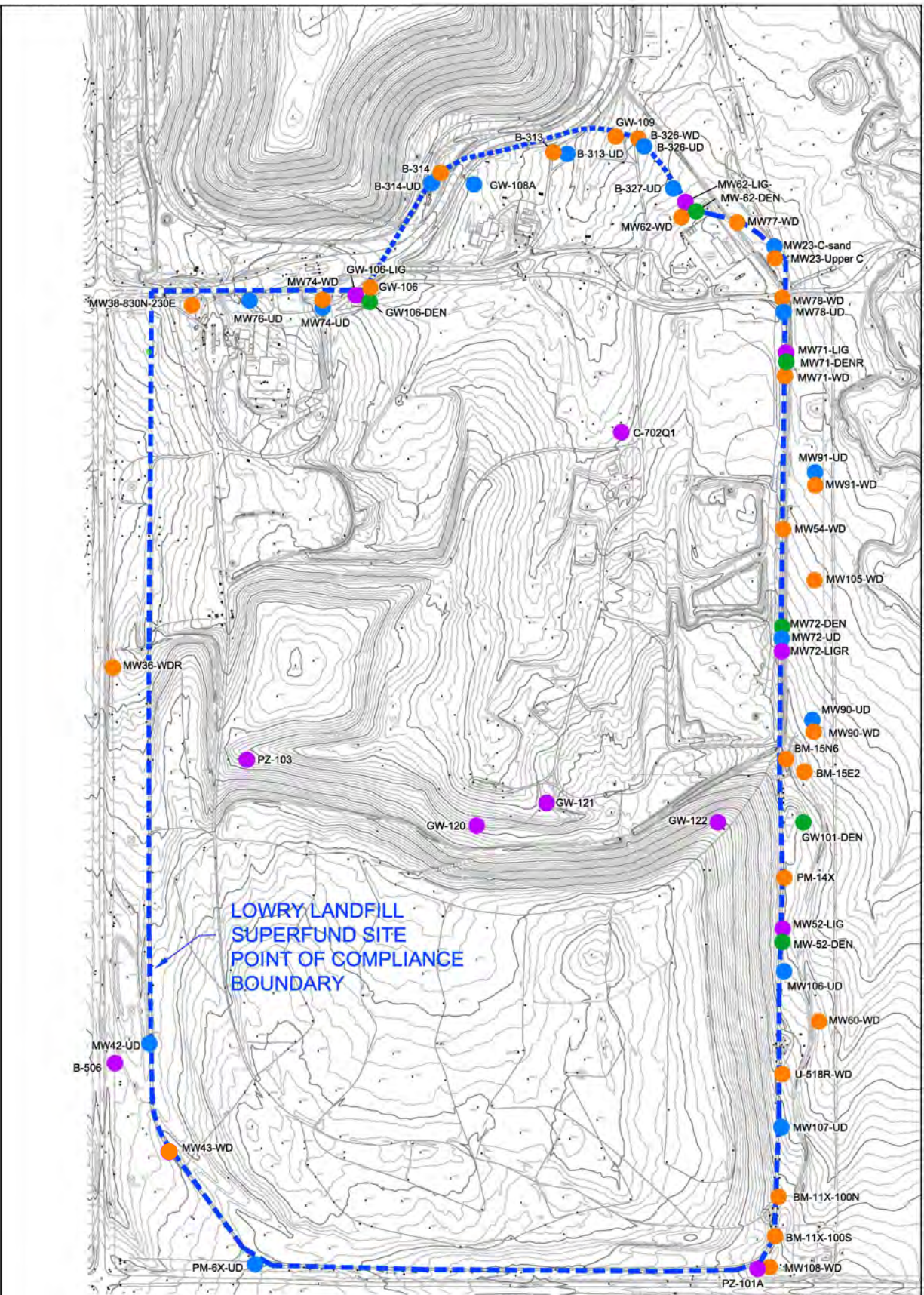


Source: Figure 5.1 (Parsons 2014)

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 5-6**  
**Gas Monitoring Probe**  
**Location Map**

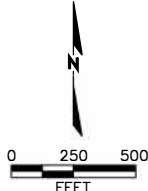




Source: Figure 6 (EMSI 2018)

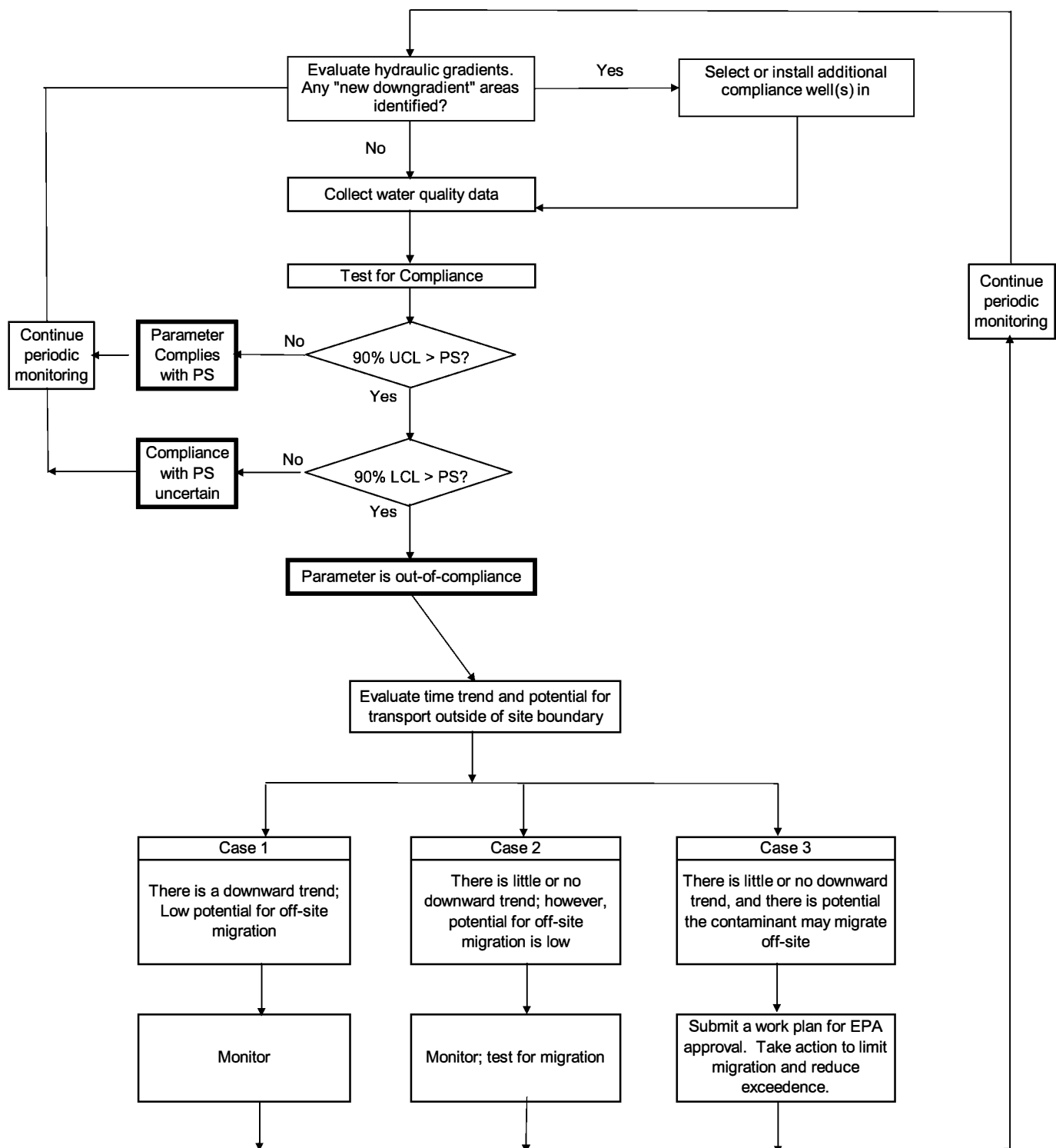
**Legend**

- Alluvium/Weathered Dawson Compliance Monitoring Well
- Unweathered Dawson Compliance Monitoring Well
- Upper Denver Compliance Monitoring Well
- Lignite Layer Compliance Monitoring Well



**LOWRY LANDFILL SUPERFUND SITE**  
 Arapahoe County, Colorado

**Figure 5-7**  
**Compliance Monitoring**  
**Network**



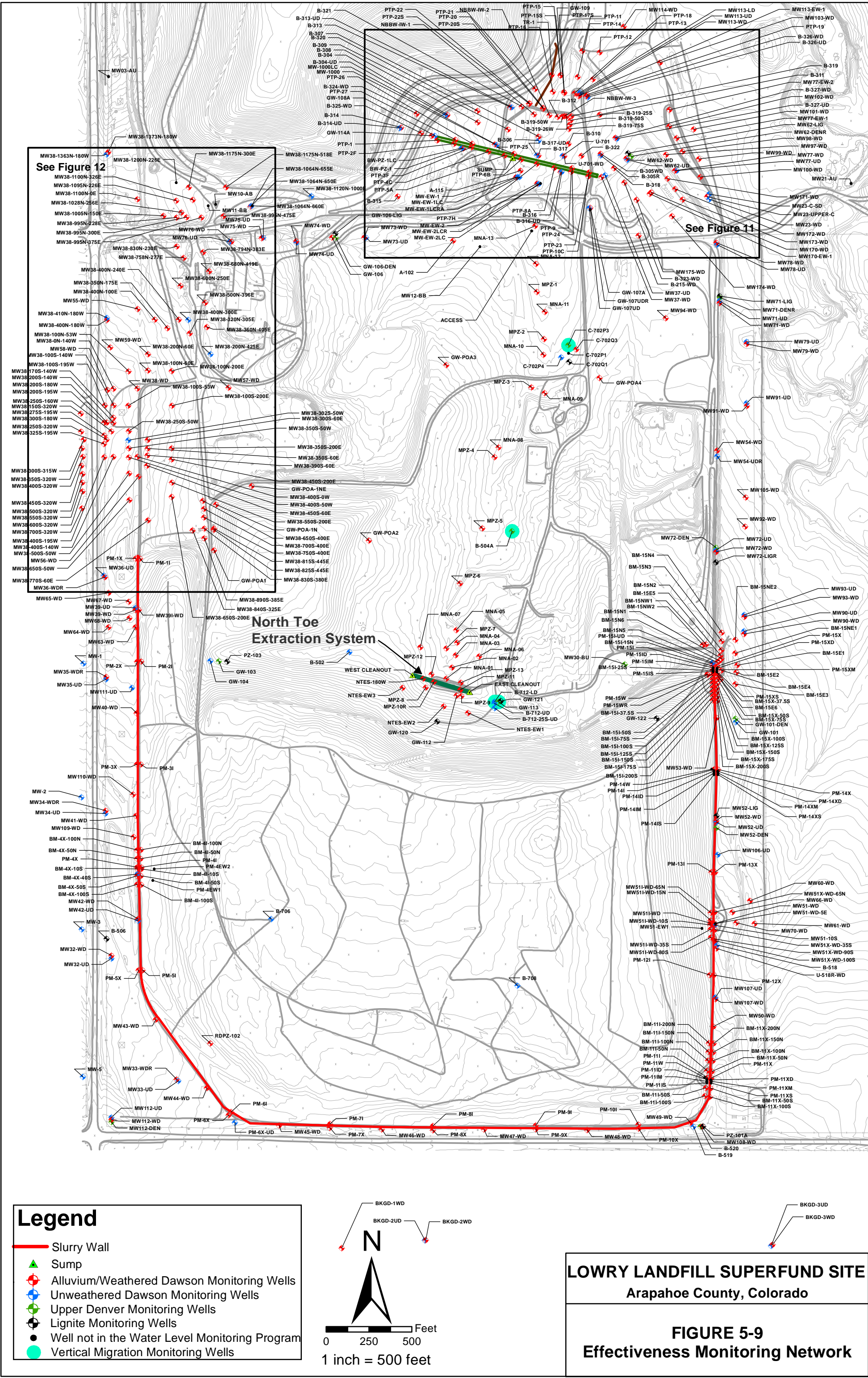
## LOWRY LANDFILL SUPERFUND SITE

Arapahoe County, Colorado

**Figure 5-8**  
**Decision Tree for Evaluation of**  
**Groundwater Compliance Monitoring Data**

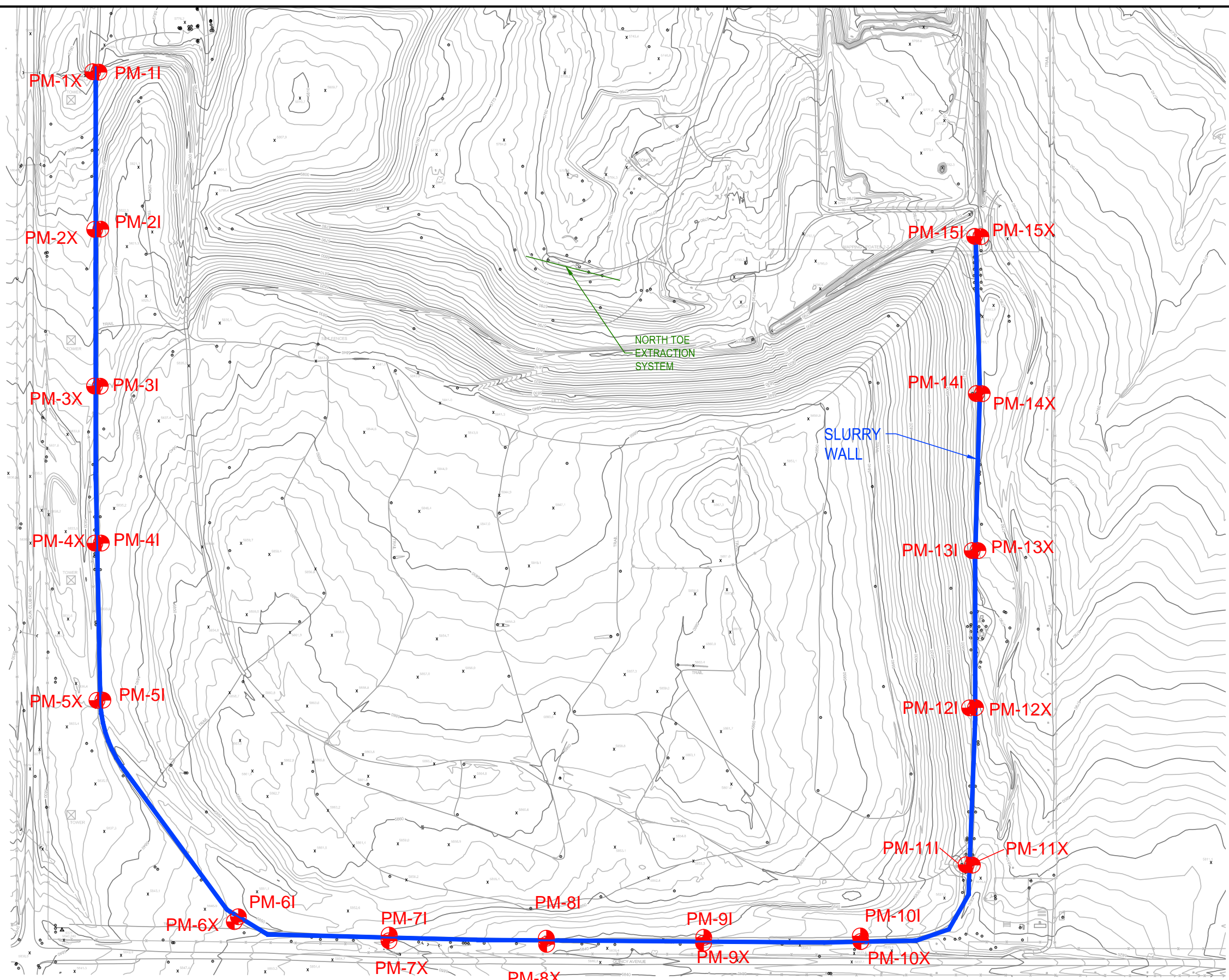
Source: Figure 3 (EMSI 2018)



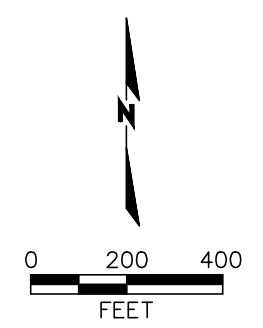




M:\clients\ELMS\LOWRY\2014\Report Maps\Fig 9-RPT-Performance-Mon\_e-s-w\_slurrywall.dwg-11X17 08/12/2014 10:26AM



**Legend**  
PM-14X ● Hydraulic gradient monitoring well pairs

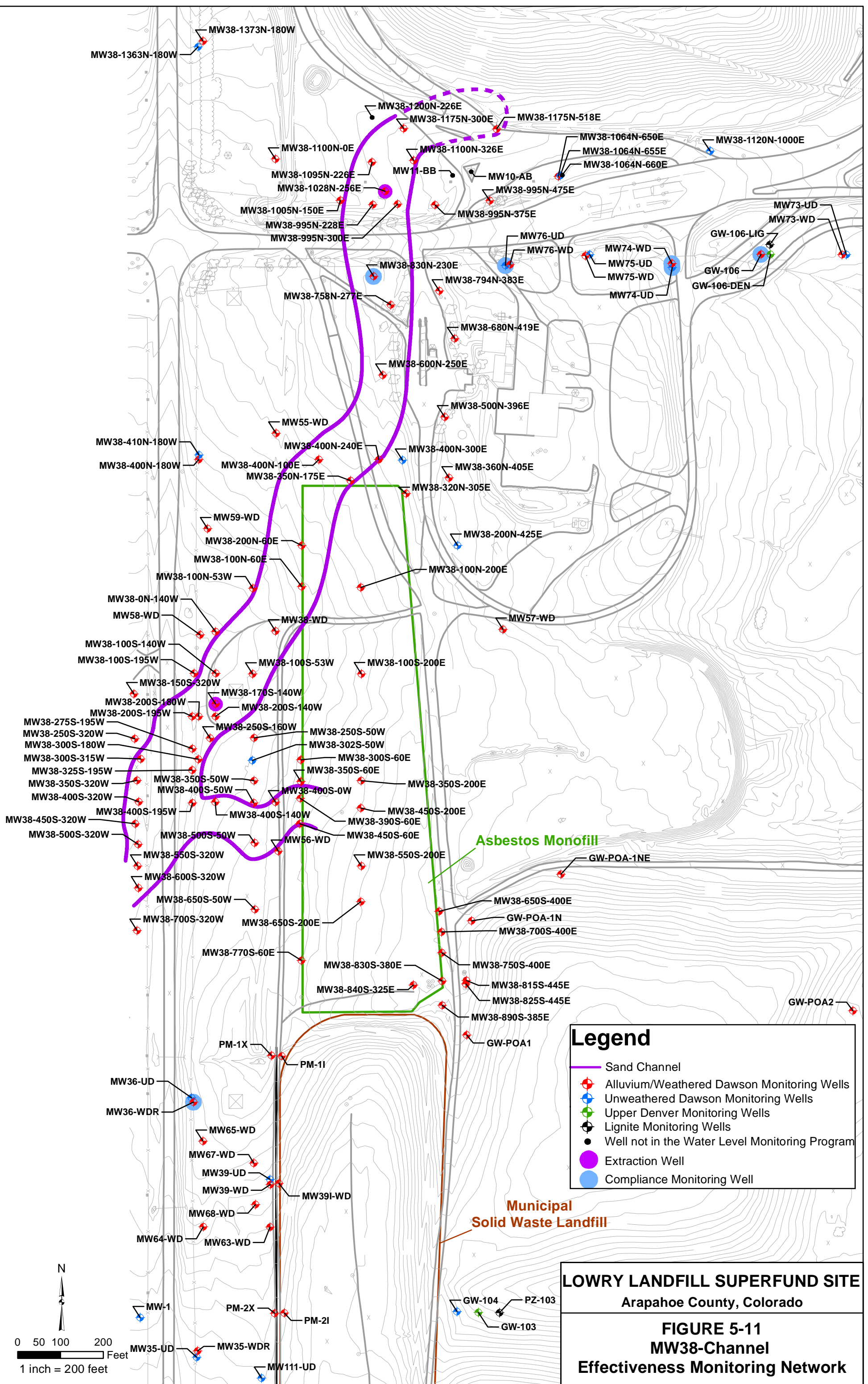


**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 5-10**  
**Perimeter Slurry Wall Effectiveness**  
**Monitoring Network**

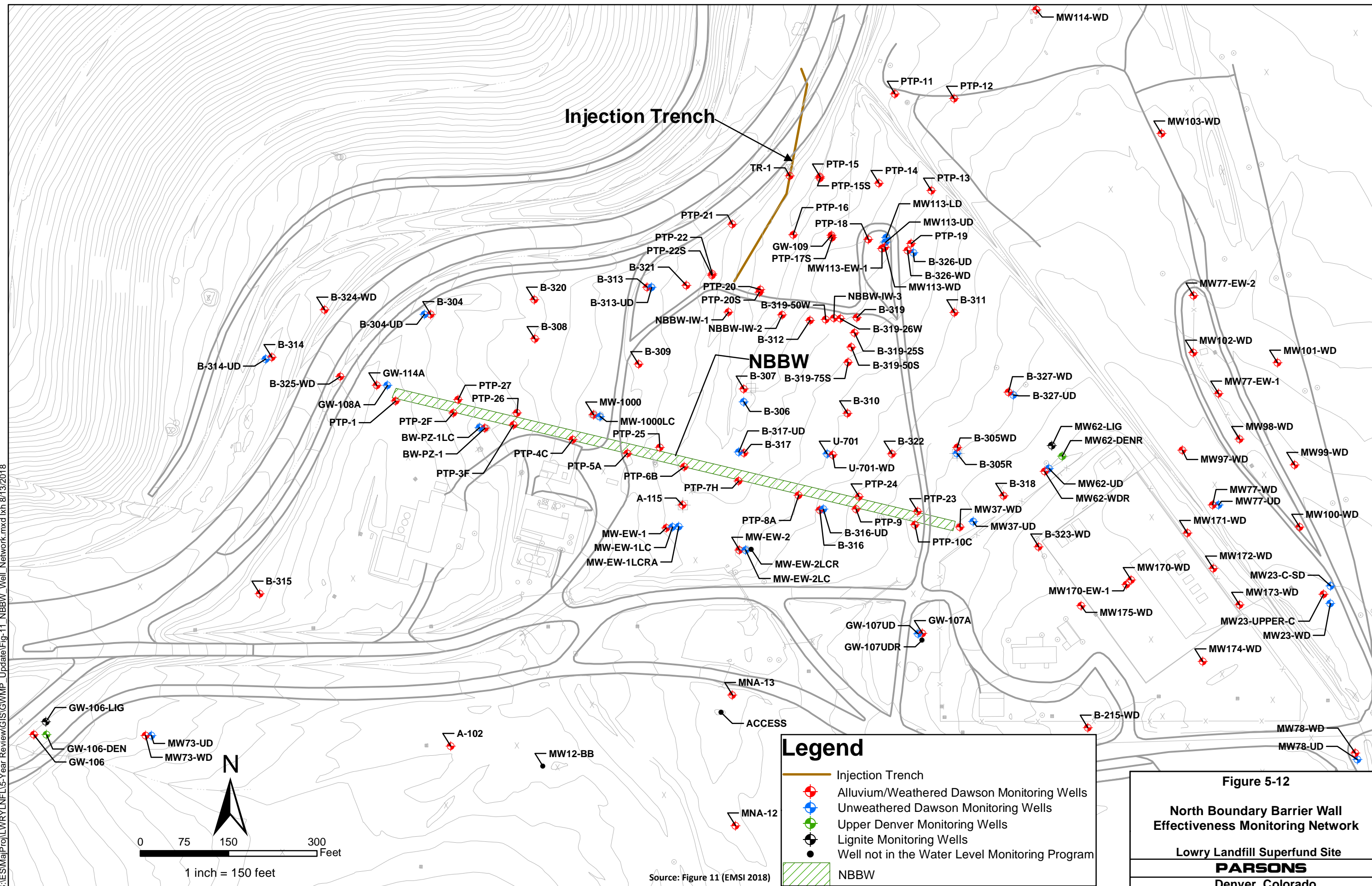
Source: Figure 9 (EMS 2018)



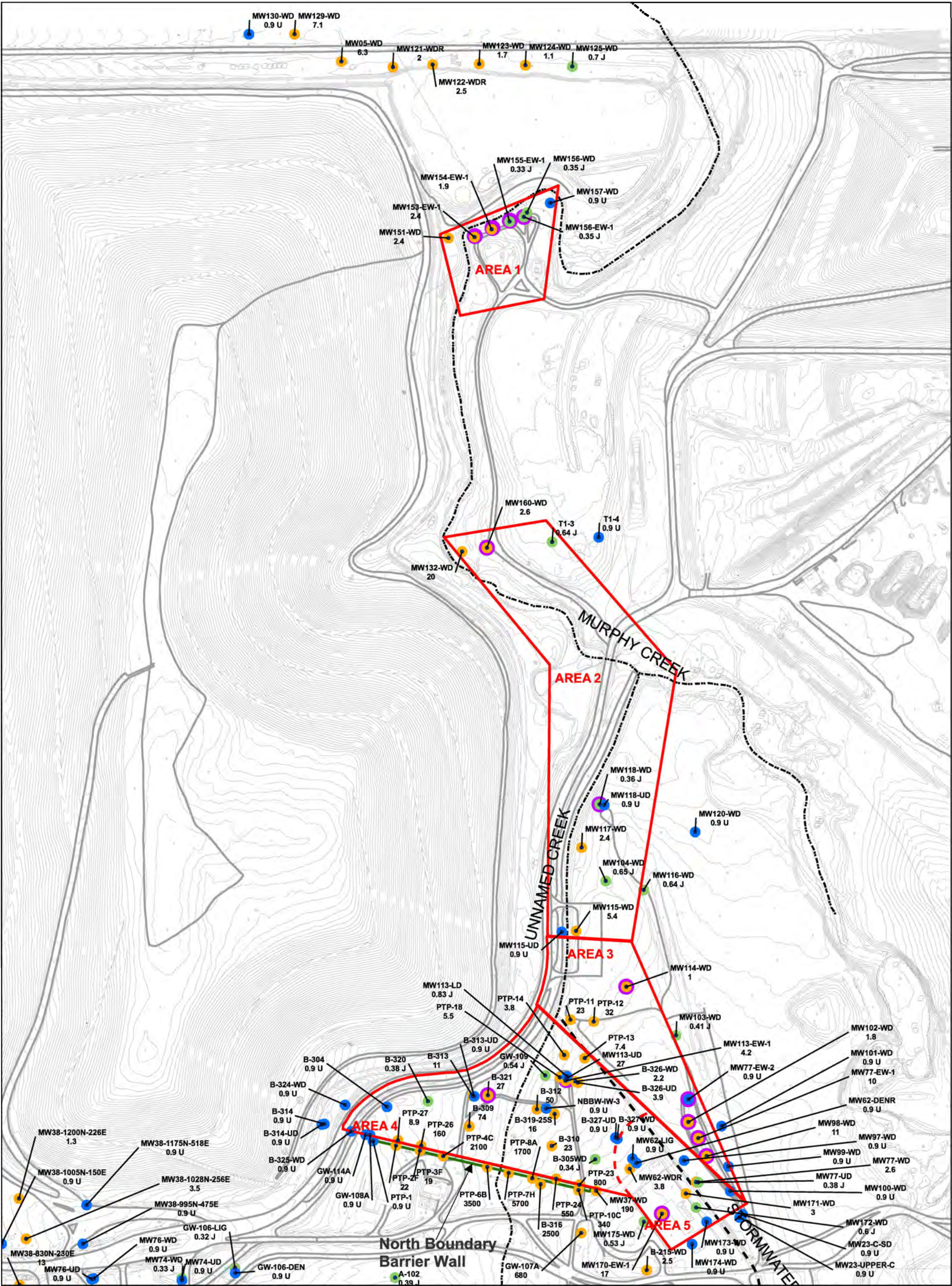




S:\ESMajProj\Lowry\NFI\5-Year Review\GIS\GWMP\_Update\Fig-11\_NBBW\_Well\_Network.mxd knt 8/13/2018







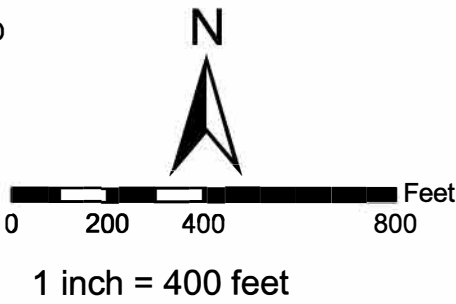
Legend

- NO 1,4-Dioxane (14X) DETECTED
- DETECTED 14X <= 0.9 ug/L PERFORMANCE STANDARD
- DETECTED 14X > 0.9 ug/L PERFORMANCE STANDARD
- EXTRACTION WELL

J = ESTIMATED VALUE  
U = UNDETECTED

Note: Extraction at MW114-WD did not start until 11/17/08

Source: Figure 4.25 (Parsons 2019)



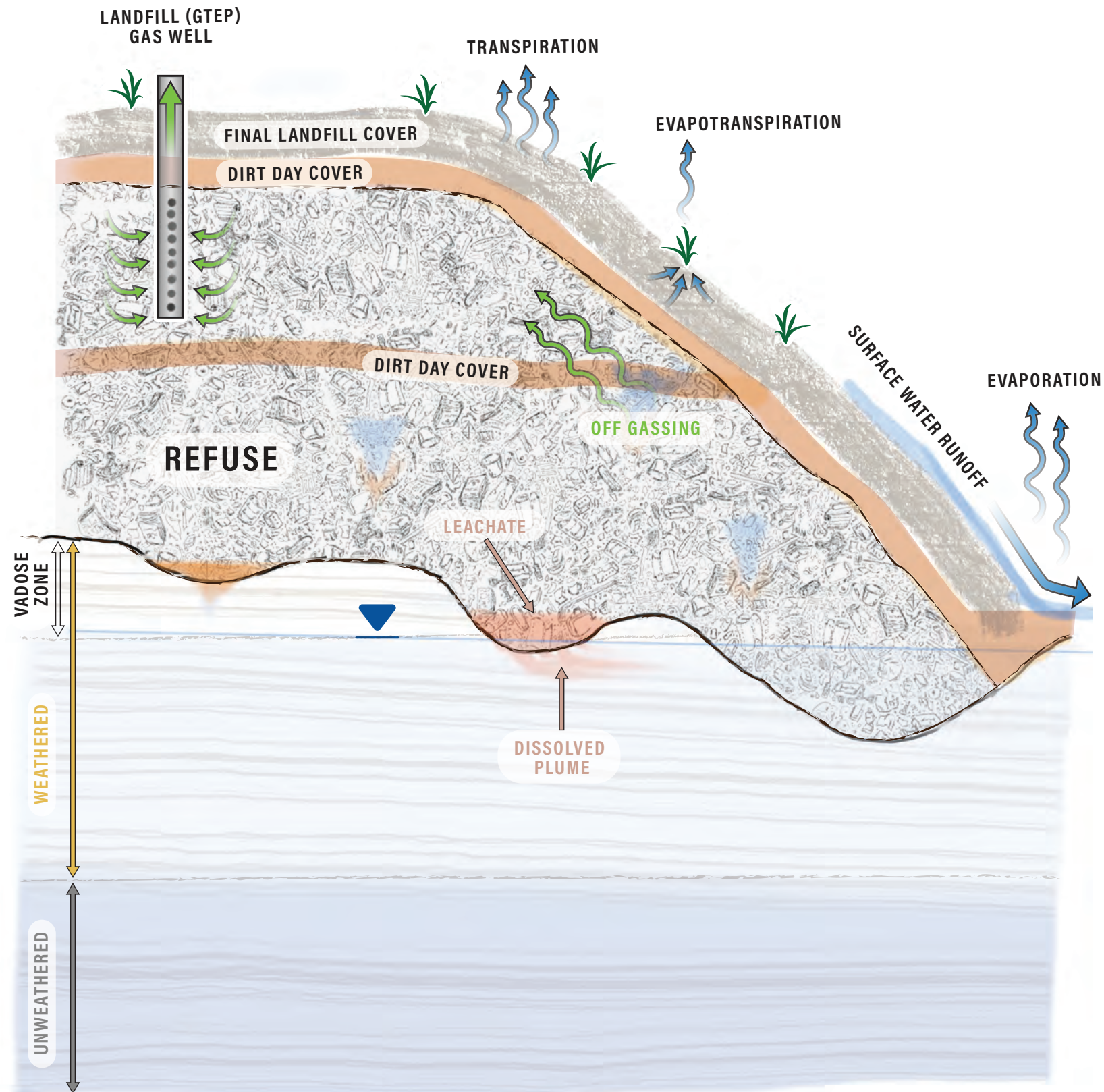
LOWRY LANDFILL SUPERFUND SITE  
Arapahoe County, Colorado

Figure 5-13  
Section 31 1,4-Dioxane Results  
Third Quarter 2018



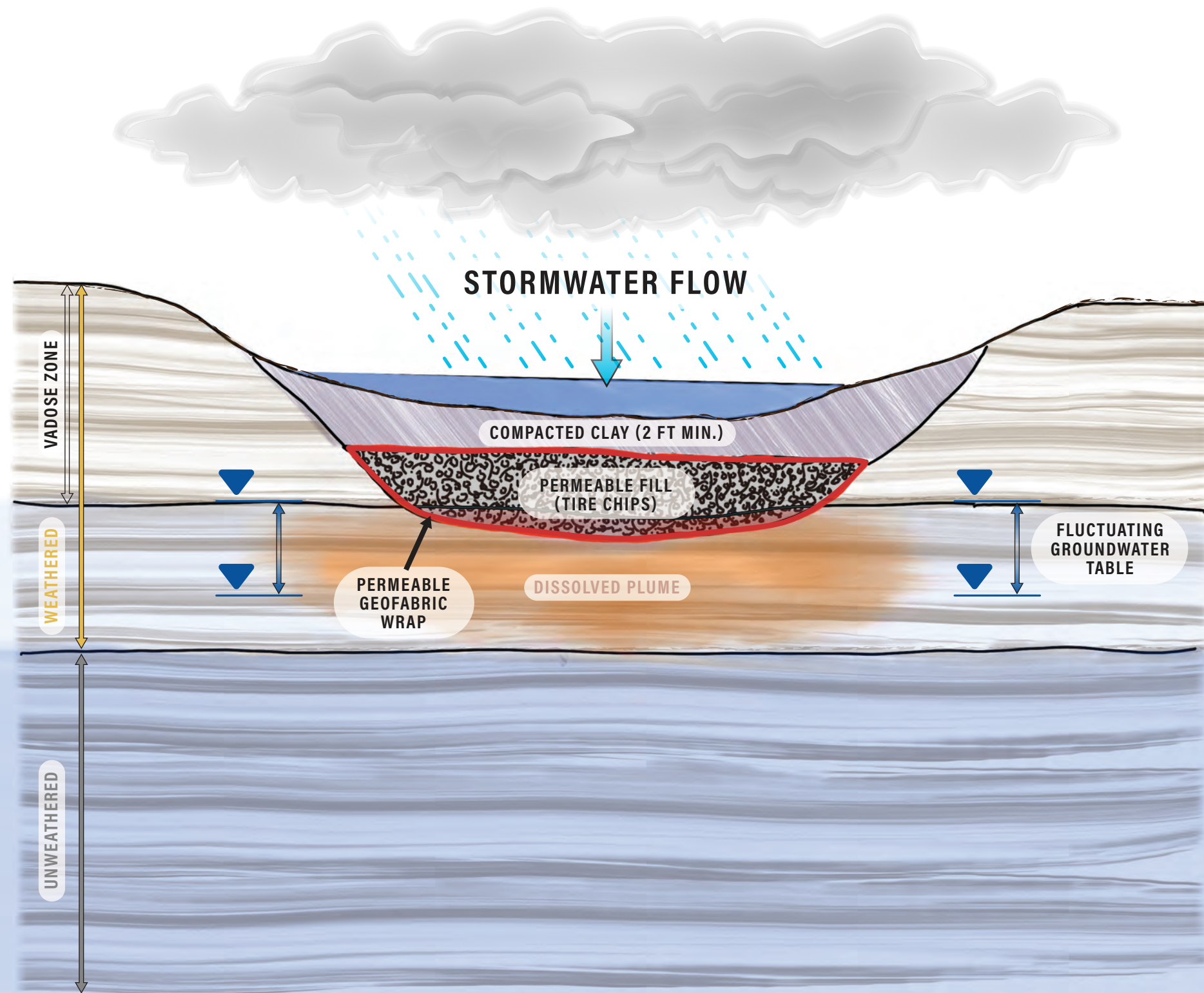
# 5-1 Landfill Cross Section

## *Remedy Components*





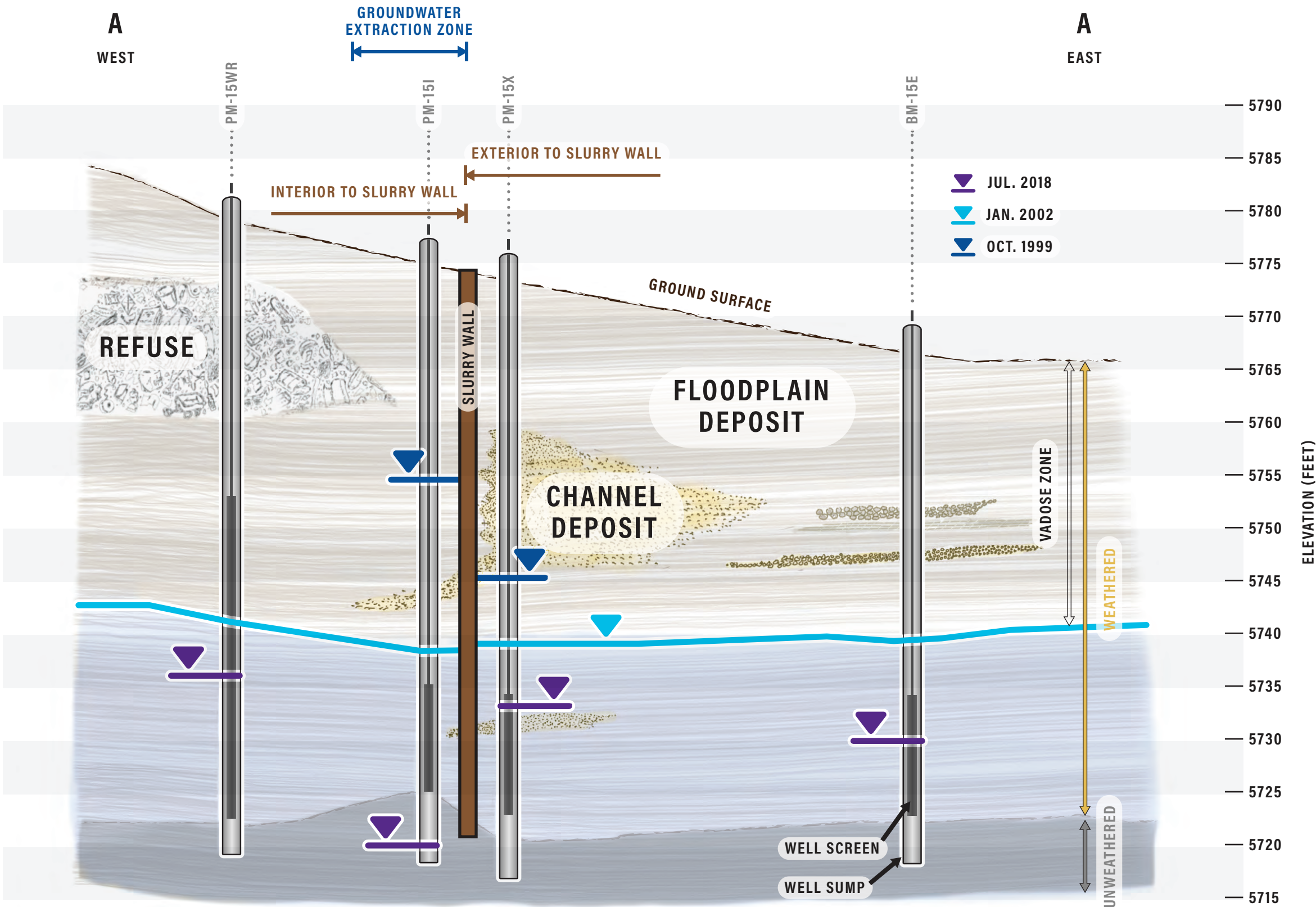
## 5-2 Surface Water Removal Action (SWRA)





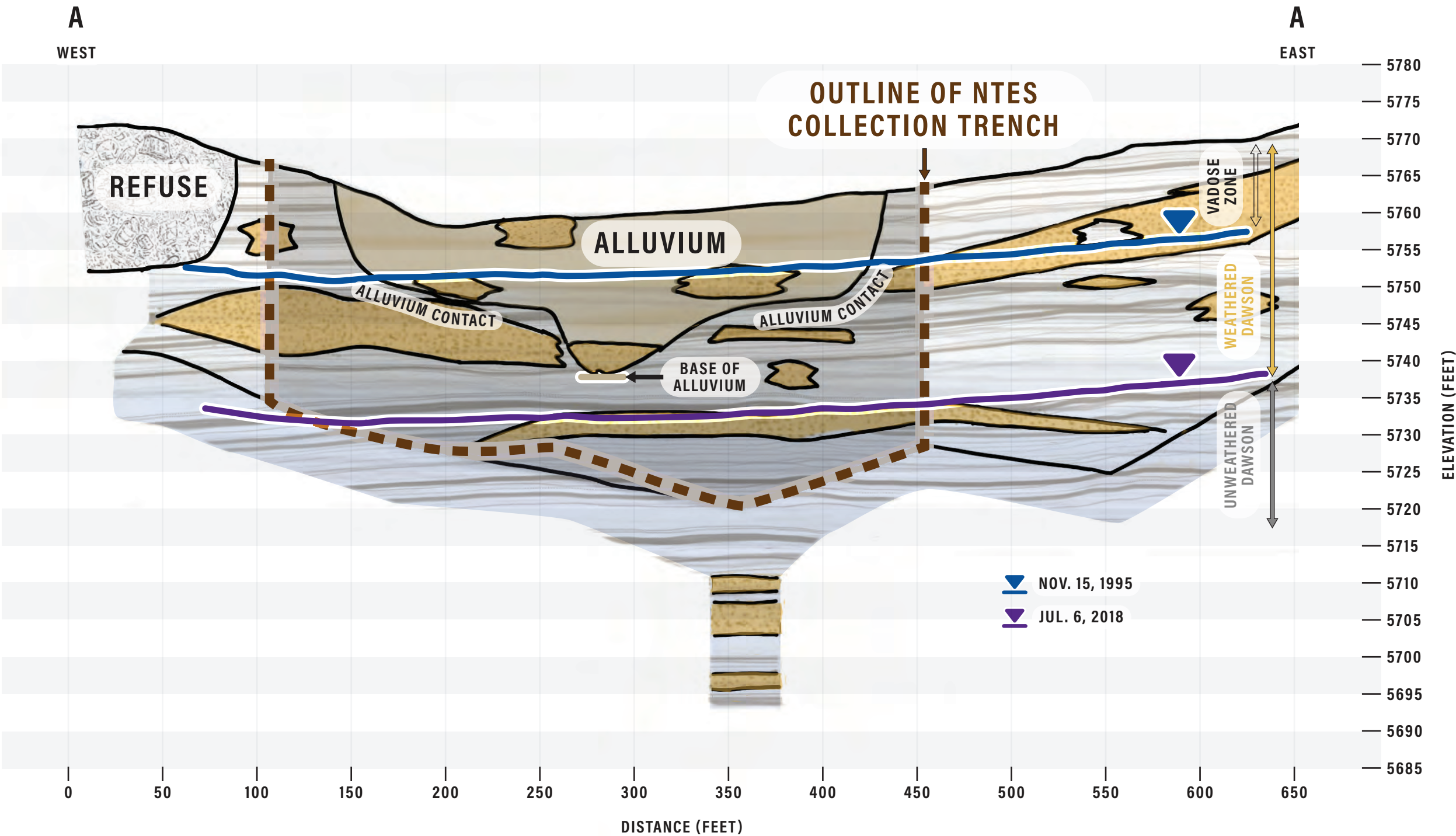
# 5-3 PM-15 / Perimeter Slurry Wall

Groundwater Extraction / Inward Gradient



# 5-4 (a) North Toe Extraction System (NTES)

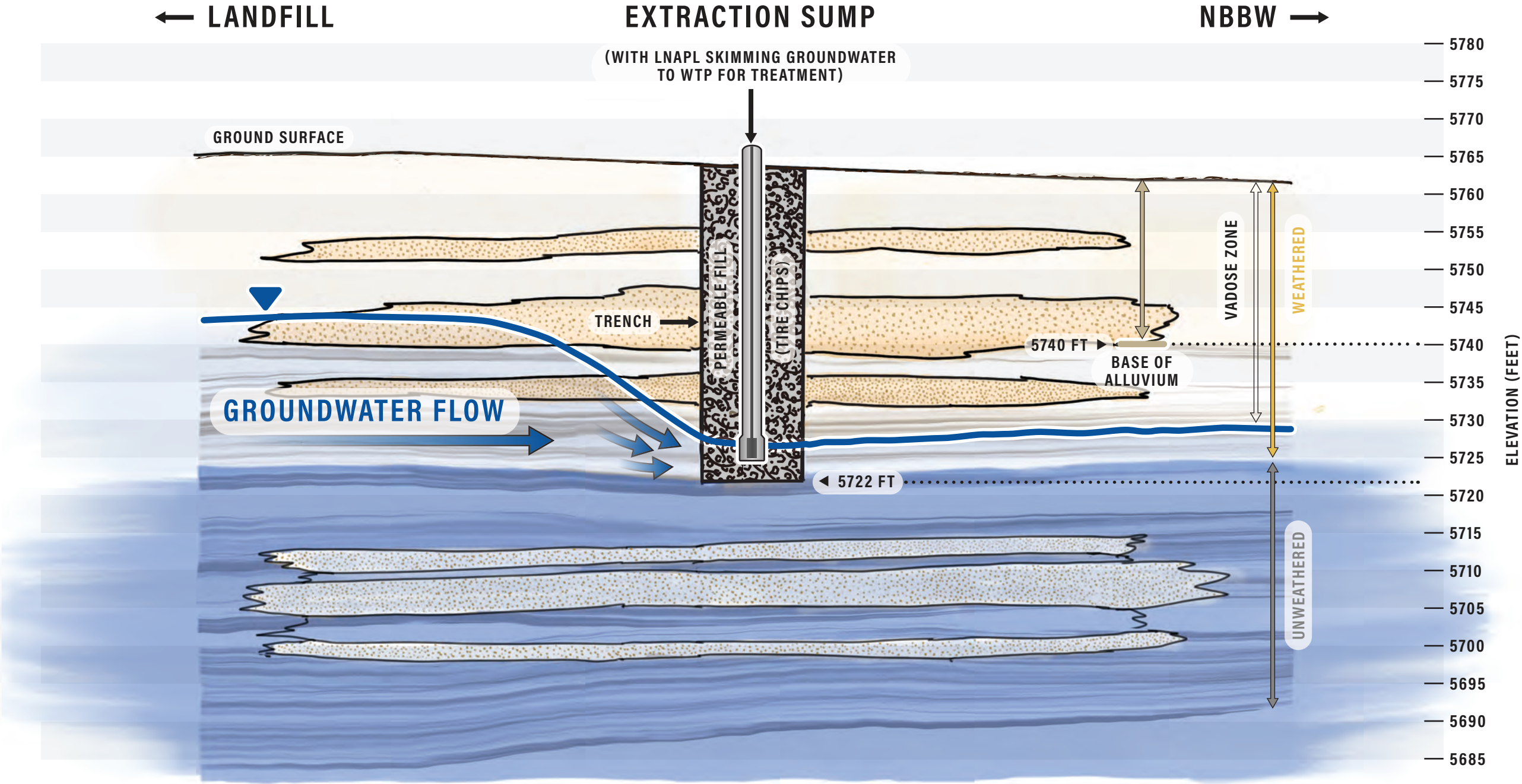
## Cross Section Profile





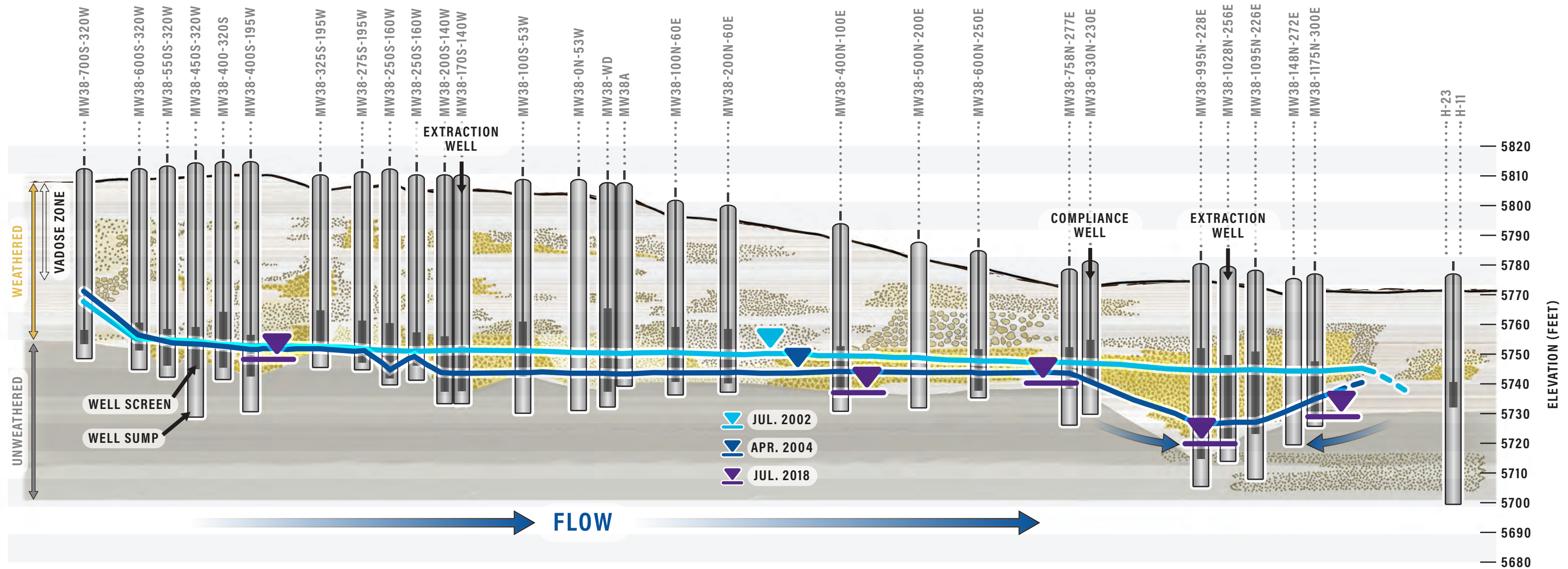
# 5-4 (b) North Toe Extraction System (NTES)

Longitudinal Profile



## Longitudinal Profile

**NORTHEAST** →





## 6.0 Nature and Extent of Contamination

This section provides an overview of the contamination at the LLSS, including the source, nature, and extent of contamination. Waste disposal procedures employed at the site including co-disposal, sanitary landfilling techniques, sewage sludge land application, and leachate land application (leachate injection), resulted in the contamination of soil, groundwater, surface water, and sediment at the site.

Additionally, gases from the buried wastes contaminated the air spaces in subsurface soil. A general overview of the site history and contamination is presented in Section 2.0. Potential surface and subsurface pathways for contaminant migration are described in Section 7.0. Exposure routes, exposure pathways, and potential receptors are discussed in Section 8.0.

As described in Section 3.0, EPA divided the site into six OUs according to the media addressed:

- OU1: Shallow groundwater and subsurface liquids
- OU2: Landfill solids
- OU3: Landfill gases
- OU4: Soils
- OU5: Surface water and sediments
- OU6: Deep groundwater

The nature and extent of contamination in each OU is described in this section. This section summarizes data collected during the RIs and is updated with more recent data as applicable. The general properties of the main contaminant groups (VOCs, SVOCs, metals, pesticides, PCBs, and radionuclides) detected at the site are described in Section 6.7.

### 6.1 OU1: Shallow Groundwater and Subsurface Liquids

OU1 includes contamination in shallow groundwater (including the alluvium, weathered and unweathered Dawson formation) and subsurface liquids. Waste pits and landfill solids within and underneath the landfill mass (source area) are the primary sources of groundwater contamination at the LLSS (Figure 6-1). As described in Section 4.2, shallow groundwater flows predominantly to the north, with components of flow to the east, west, and south. At the site, the shallow-most geologic unit is the Dawson formation. North of the site, the Dawson formation phases into the Denver formation as the shallow-most geologic unit although notable changes in the sediments are not observed and this difference in delineation does not have a notable impact on the hydrogeology.

Contamination in OU1 was investigated as part of the 1992 RI for OUs 1 and 6 (HLA 1992); the RI results and conclusions were summarized in the ROD (EPA 1994). The ROD grouped data and analysis into the following categories: (1) waste pit liquid within the source area; (2) saturated refuse within the source area; (3) shallow groundwater in the weathered system; (4) shallow groundwater upgradient of the source area; (5) shallow groundwater in the weathered and unweathered systems outside the source area; and (6) deep groundwater. Tables 6-1 through 6-5 of the ROD present the chemical concentration data summary for each grouping. Deep groundwater is discussed in Section 6.6 below, as part of OU6.

Additional data are included where available to provide an evaluation of current site conditions and to supplement the summary presented in the ROD. Sources of more recent data include the groundwater data collected as part of the ongoing groundwater compliance and monitoring program, as well as

localized investigations such as the North End Investigation, that were completed to investigate portions of the site.

#### 6.1.1 Waste Pit Liquids and Saturated Refuse Within the Source Area

Between 1964 and 1980, Lowry Landfill accepted solid and liquid municipal and industrial wastes, including hazardous substances. Prior to 1976, trenches would first be filled with liquid waste, and then backfilled with solid waste. This method was known as co-disposal. Once filled with waste, a trench would then be covered with borrow soil from the site. The co-disposal technique was reversed in 1976. The solid waste was placed first in the trench and compacted, then the trench was filled with liquid waste. Once the trench was full, it was covered with borrow soil. The co-disposal method was changed to promote more immediate absorption of the liquids into the solid waste and to minimize potential fire hazards created by the open trenches of liquid. The co-disposal waste pits are located in Section 6 within the western two-thirds of the landfilled area and FTPA (Figure 3-1).

The volume of liquid within the saturated waste pits was estimated in the ROD to be approximately 95 million gallons (EPA 1994). Over time, some of the contaminated liquid originally placed into the pits seeped out of the pits and mixed with the surrounding solid wastes, groundwater, and surface water. Illustration 3-1 shows the basic construction of the waste pits and the migration of the contaminants into the surrounding soil and groundwater.

Immiscible-phase liquids (both LNAPL and dense non-aqueous phase liquid [DNAPL]) were identified in 10 of the approximately 70 waste pits. The amount and type of LNAPL and DNAPL varied considerably between well points and even between measurements in the same well point. Figure 6-2 shows the waste pits and the waste pit well points. Based on sampling results, the extent of mobile-phase NAPL appeared to coincide with the horizontal extent of the waste pits and to the vertical extent of the weathered hydrogeologic system. The presence of NAPL has decreased over time and is now rarely observed in monitoring wells. The NTES, which was installed in 1998, collects NAPL from the Lowry Landfill. A measured product thickness of greater than six inches is used to trigger NAPL extraction at the NTES. The last LNAPL extraction from the NTES took place September 13, 2011 (EMSI and Parsons 2019b). Visual inspection of the groundwater pumped from the NTES to the WTP in 2019 found no globules present in the pumped groundwater, indicating no LNAPLs or DNAPLs were present.

The waste pits and associated liquids contain the highest average concentrations of VOCs, SVOCs, metals, and radionuclides as compared to other contaminated liquid at the site. Analytical results from the waste pit liquid samples collected as part of the RI indicated a high degree of spatial variability across the site. Toxicity Characteristic Leaching Procedure (TCLP)<sup>23</sup> analyses were performed on waste pit liquids and waste solids. Several VOCs, SVOCs, and one pesticide and one metal were detected at or above regulatory levels in the extract from these samples. Based on Resource Conservation and Recovery Act toxicity characteristic testing, waste pit solids and liquids were determined to be hazardous.

Saturated refuse samples were collected from three borings within the source area. VOCs, SVOCs, and metals were detected. The saturated refuse (saturated solids outside of the waste pits) contained

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<sup>23</sup> TCLP is a chemical analysis procedure used to determine whether there are hazardous elements present in waste based on toxicity. The test involves a simulation of leaching through a landfill to determine the mobility of organic and inorganic chemicals in the waste.



similar contaminants to those detected in the waste pit liquid, waste pit solids, and source area shallow groundwater, but at similar or lower concentrations. The volume of liquid within saturated refuse was estimated to be approximately 14 million gallons (EPA 1994).

Currently, groundwater monitoring occurs at the perimeter and downgradient of the landfill mass with the objective of monitoring for potential migration of contamination from the landfill mass and waste pits north of the landfill mass. Groundwater samples are not collected from within the landfill mass and waste pits. A comprehensive groundwater sampling event was conducted in 2018; sampling locations are shown on Figure 6-3. This sampling event is presented in detail in PWT and Tetrattech 2020. Two monitoring wells screened beneath the landfill mass (B-706 and B-708) and seven wells (MPZ-7, MPZ-10, MPZ-11, MPZ-12, MPZ-13, GW-120, and GW-121) near, but upgradient of the NTES, were sampled. 1,4-dioxane and acetone were detected in the monitoring wells screened beneath the landfill mass sporadically at low estimated concentrations and were detected near the NTES. Extraction wells NTES-EW1, NTES-EW2, and NTES-EW3 contained concentrations of 1,4-dioxane and VOCs.

Although current samples collected from the two monitoring wells screened beneath the landfill mass contained sporadic low estimated concentrations of VOCs, it is assumed that liquids and groundwater within the landfill mass continue to be contaminated at concentrations above performance standards.

#### 6.1.2 Shallow Groundwater within the Site Boundary

Waste disposal procedures employed at the site other than co-disposal and sanitary landfilling techniques included sewage sludge land application and leachate land application and injection on the northern and north-central portions of Section 6. These disposal areas are shown on Figure 3-2. The sludge and liquid waste contaminated the soil, shallow groundwater, surface water, sediment, and soil gas at the site. In addition, groundwater contaminated by the waste pit liquids and saturated refuse within the landfill mass has migrated outside of the main source area (Illustrations 3-1 and 3-2).

In general, compounds detected in shallow groundwater within the site boundaries are similar to those detected in samples from the waste pit liquid. However, the concentrations of these compounds in shallow groundwater are generally lower than concentrations detected in the waste pit liquid. VOCs are the most prevalent compounds present in the shallow groundwater within the site boundaries, but SVOCs, pesticides, PCBs, and other compounds are also detected. In addition, radionuclides, trace metals, and inorganics are frequently present in samples collected from site monitoring wells.

The maximum concentrations of 1,4-dioxane and VOCs are detected immediately upgradient of the NTES and within the bed of the unnamed creek from the NTES to the NBBW. The extent of 1,4-dioxane and VOCs (as indicated by PCE and 1,1-DCA) are shown on Figures 6-4 and 6-5. Except for 1,4-dioxane, the horizontal extent of contamination is contained within the site boundaries by the perimeter slurry wall, NTES, NBBW, and MW38 extraction systems. The vertical extent of contamination in this area extends partially into the unweathered lithology.

The RI estimated the volume of potentially contaminated shallow groundwater within the site boundary to be in the range of 900 million to 2 billion gallons. The broad range was presented because of differing methods of estimating the volume of contaminated shallow groundwater.

### 6.1.3 Shallow Groundwater Upgradient of the Source Area

The RI included a comprehensive investigation of upgradient monitoring wells (south of Lowry Landfill and outside of the perimeter slurry wall). Parameters detected in samples from the upgradient groundwater monitoring wells (B-519, B-520, MW-3, MW04, MW-5, MW22, U-509, and U-510) included organics, trace metals, and radionuclides. The organics detected in samples from upgradient monitoring wells were common laboratory contaminants, and the concentrations were most likely indicative of laboratory artifacts or cross-contamination during sampling (HLA 1992). One perimeter monitoring well, U-510, had confirmed organic contamination, indicating contaminant migration to the north, toward the southern boundary of the LLSS. Further sampling of monitoring well U-510 (screened from 48 to 58 feet bgs) revealed organic and inorganic compounds including PCE, TCE, 1,1,1-TCA, and 1,1-DCA.

The WSDs sampled three background wells (BKGD-2UD, BKGD-2WD, and BKGD-3WD, shown on Figure 5-9) in July and November of 2018. No analytes were detected in the wells except low concentrations of acetone in detected in BKGD-2UD and BKGD-2WD (November 2018) and nitrogen as nitrate in BKGD-3WD (July 2018). Acetone is a common laboratory contaminant (as verified by its presence in a background well) and nitrate is ubiquitous in the area.

Groundwater contamination, in particular 1,4-dioxane and VOCs, have been detected at concentrations above the performance standards outside the perimeter slurry wall. When installed, the slurry wall did not fully encompass the known extent of groundwater contamination; however, contingency measures including extraction wells and air sparging systems have been implemented to treat and contain the contamination outside the slurry wall. In 2018, 1,4-dioxane was detected at 1.6 µg/L at monitoring well MW46-WD, south of the LLSS and outside of the slurry wall; this detection exceeds the performance standard for 1,4-dioxane (0.9 µg/L). However, 1,4-dioxane was not detected in the other exterior monitoring wells sampled in the first half of 2019 (EMSI and Parsons 2019b).

Monitoring wells surrounding the slurry wall are monitored as described in the GWMP (EMSI and Parsons 2018) and the results are reported semiannually in the SSRs. The effectiveness of the slurry wall is determined by evaluating the presence of an inward hydraulic gradient, using 15 paired monitoring wells inside and outside of the perimeter slurry wall and by evaluating water quality data for five indicator compounds (1,1,1-TCA, 1,1-DCA, TCE, PCE, and 1,4-dioxane) obtained from wells located outside of the slurry wall (Figure 5-10). The presence of an inward hydraulic gradient and no trend or a decreasing trend in water quality data indicates the slurry wall is effective at containing site contaminants. Conversely, the presence of an outward hydraulic gradient or increasing water quality trend indicates the need for investigation to determine if there is an issue with containment. The SSR for the first half of 2019 concluded that the slurry wall is effective at containing groundwater within the eastern, southern, and western limits of the landfill footprint (EMSI and Parsons 2019b). The five indicator compounds were not detected above the performance standards in the monitoring wells used for the effectiveness monitoring.

### 6.1.4 Shallow Groundwater at the Point of Compliance

The WSDs regularly sample groundwater at the POC and outside of the site boundary as part of the groundwater monitoring and compliance program. Groundwater samples are collected from wells near the POC, and detected concentrations are compared to the performance standards. Wells containing concentrations of the 29 indicator chemicals at concentrations exceeding the performance standards are further evaluated, using the evaluation decision tree and criteria summarized in Section 5.11 and



detailed in the GWMP (EMSI and Parsons 2018). This section summarizes results and conclusions of the SSR for the first half of 2020 (EMSI and Parsons 2020).

In 2020, water quality for one or more compliance monitoring parameters at 8 of the 60 compliance monitoring locations exceeded performance standards (EMSI and Parsons 2020). The parameters found to exceed performance standards included 1,4-dioxane, chloroform, nitrate, and PCE. Statistically-based compliance determinations could not be made for nitrite, nitrate, or TCE at 6 of these 8 monitoring wells and for 1,4-dioxane at one additional compliance well (MW106-UD).

The eight wells determined to be statistically out of compliance are summarized below.

Well	Compound	Compliance Decision
B-313	1,4-Dioxane	Out of Compliance
B-326-UD	1,4-Dioxane	Out of Compliance
B-326-WD	1,4-Dioxane	Out of Compliance
BM-11X-100N	PCE	Out of Compliance
BM-15N6	Nitrate	Out of Compliance
MW38-830N-230E	1,4-Dioxane, Chloroform	Out of Compliance
MW62-WDR	Nitrate	Out of Compliance
MW77-WD	1,4-Dioxane	Out of Compliance

The above compliance determination summary list is the same as that of the second half of 2019, with exception of two wells: well B-326-WD was previously potentially out of compliance for 1,4-dioxane and is now out of compliance for 1,4-dioxane; and well MW62-WDR, which was previously out of compliance for 1,4-dioxane is now indeterminant and potentially out of compliance. The concentrations of the out of compliance compounds in the specific previously indeterminant wells were detected at concentrations similar to the performance standards. The similarity of the detected concentrations and the performance standards indicates that the wells may oscillate between the compliance determinations from one reporting period to the next.

1,4-dioxane occurs in excess of its performance standard in five NBBW-area compliance monitoring wells (B-313, B-326-UD, B-326-WD, MW62-WDR, and MW77-WD) (Figure 6-6). The WSDs are conducting detailed supplemental evaluations of the effectiveness of the NBBW containment system and the response actions that have been implemented in this area. If necessary, the WSDs will evaluate possible enhancements to the remedial and response actions currently in place to address the 1,4-dioxane detected above the performance standard. These additional evaluations will be conducted as part of the NBBW Containment System Evaluation (CSE) and Optimization Study, which will utilize results from the NBBW cessation pilot test and a numerical groundwater model currently in development by the WSDs (EMSI 2020b). In the meantime, 1,4-dioxane north of the NBBW will continue to be captured by pumping at the NBBW extraction wells and the North End response action extraction wells.

Nitrate occurs in excess of its performance standards in compliance monitoring wells MW62-WDR and BM-15N6. Well MW62-WDR is located along the northern boundary of the site, in an area where sewage sludge was historically land-farmed. Statistical testing of potential temporal trends in the results (Appendix C-3.2 of the SSR [EMSI and Parsons 2020]) indicates that there is no significant trend (increasing or decreasing) in the nitrate concentrations in monitoring well MW62-WDR.

Nitrate occurs in well BM-15N6 at concentrations greater than its performance standard. Well BM-15N6 is located on the northeastern end of the perimeter slurry wall. Like MW62-WDR, well BM-15N6 is in an area where sewage sludge had historically been land-farmed. EPA positioned the compliance boundary within the land farming area such that it straddles the land farming area. That, coupled with an absence of 1,4-dioxane and only low-level detections of VOCs (below performance standards) since 2003 in this well, would indicate the source of nitrates is not from the migration of contamination from the landfill mass or waste pit; rather, it is likely from the past land farming activities inside and outside the compliance boundary (EMSI and Parsons 2019b). Nitrate has been observed in surrounding wells BM-15N2 (43,000 µg/L), BM-15NE1 (26,000 µg/L), BM-15N5 (68,000 µg/L) and BM-15N1 (25,000 µg/L) in the first half of 2017 and in BM-15I-15N (54,000 µg/L), BM-15I-50S (9,300 µg/L), and BM-15X-50S (38,000 µg/L) in October 2018.

The spatial randomness of nitrate detections in and around well BM-15N6 as compared to other compliance wells in this vicinity is similar to that observed near the NBBW where sewage sludge was land-farmed. The randomness is likely attributable to a number of hydrogeochemical variables associated with the leaching, transport, and attenuation of nitrates that can differ significantly from location to location. Nitrate concentrations can also fluctuate with precipitation and rate of groundwater pumping from the PM-15 Area wells (EMSI and Parsons 2019b). Based on these observations, EPA has determined there is no additional action required regarding these nitrate and nitrite observations and that they do not present a risk to human health or the environment.

Chloroform and 1,4-dioxane concentrations in monitoring well MW38-830N-230E exceed their groundwater performance standards. No temporal trends in the concentrations of these chemicals were identified in this well. This well is located along the POC at the north end of the MW38 channel. The hydraulic gradient within the channel at this location is to the north toward extraction well MW38-1028N-256E so migration of these chemicals crosses the POC by approximately 200 feet before reaching the extraction well for subsequent removal. As part of the groundwater containment remedy for the site, groundwater extraction is conducted from the MW38 channel at two locations, including a location approximately 200 ft north of well MW38-830N-230E, which is downgradient from and beyond the POC relative to the compliance monitoring well. Therefore, although these chemicals may migrate across the POC, impacted groundwater is hydraulically contained within, and removed from, the sand channel in the area immediately north of well MW38-830N-230E (EMSI and Parsons 2019b).

#### 6.1.5 Shallow Groundwater within North End Area

The groundwater north of the site boundary has been regularly monitored as part of the GWMP and investigated as part of the North End investigation in 2019. This section summarizes results and conclusions from the first half 2020 SSR (EMSI and Parsons 2020) and the North End investigation report (EMSI and CDM Smith 2020b). The North End Area is shown on Figure 6-7.



Groundwater samples collected from shallow and deep groundwater monitoring wells were analyzed for 1,4-dioxane, VOCs, nitrate, and major anions and cations. The only compound of concern that exceeded a groundwater performance standard north of the LLSS was 1,4-dioxane.

In 2005, the Colorado Water Quality Control Commission established a new groundwater standard for 1,4-dioxane. At that time, improvements in laboratory methods allowed samples to be analyzed for 1,4-dioxane at the new standard, which resulted in the detection of 1,4-dioxane north of the site.

Colorado's groundwater standard for 1,4-dioxane has been revised since 2005 and the current standard is now 0.35 µg/L. Current best available analytical technology is not able to detect 1,4-dioxane at this concentration in environmental samples from the LLSS due to naturally occurring water quality beneath and north of the site resulting the current laboratory defined site-specific project quantitation limit and performance standard for the LLSS of 0.9 µg/L. This concentration is protective and aligns with the laboratory method detection limits and reporting limits in the annual PQL study. As described in Section 5.11, the PQL was last reviewed in December 2019 (EMSI and Parsons 2020b) and will be reviewed annually, as required by the Consent Decree, to address performance standards (or permitted discharge limits for the WTP) that are less than the PQL. The performance standard for 1,4-dioxane may be adjusted if the PQL study concludes that a lower standard would be technically feasible. The potential risks associated with exposure to 1,4-dioxane at or above 0.9 µg/L are discussed in Section 8.3.

The extent of 1,4-dioxane in the North End Area exceeding the performance standard is shown on Figure 6-7. Sands in the shallow weathered groundwater unit (approximately 50 feet deep) serve as preferential groundwater pathways that generally align with the westernmost branch of Murphy Creek. The 1,4-dioxane plume delineated on Figure 6-7 occurs within these preferential pathways. 1,4-dioxane concentrations were detected in shallow groundwater north of Section 31 at a maximum concentration of 7.4 µg/L at monitoring well MW129-WD. Concentrations were highest in Section 31 and generally decreased to non-detect at the northern end of the plume south of East Mississippi Avenue and east of Gun Club Road. 1,4-dioxane has not been detected in groundwater north of the LLSS below a depth of approximately 50 feet bgs (EMSI and CDM Smith 2020b).

As described in Section 5.13, North End response actions were implemented as a contingency measure on site and north of the site boundary in response to the discovery of 1,4-dioxane in this area.

Groundwater extraction wells were installed in five areas (Areas 1 through 5) to reduce off-site migration of 1,4-dioxane, reduce the mass of 1,4-dioxane north of the site, and to bring compliance wells into compliance with performance standard (Figure 5-13). Charts of 1,4-dioxane concentrations over time are included in Attachment E of the first half 2020 SSR (EMSI and Parsons 2020). The charts indicate declining concentrations of 1,4-dioxane in the North End monitoring wells.

## 6.2 OU2: Landfill Solids

This section discusses landfill solids in both the landfill mass and the FTPA. The primary sources of contamination in landfill solids are the waste pit liquids and the municipal refuse. Characterization of the landfill solids was conducted during the RI for OUs 2 and 3 (HSI and CDM 1993). The landfill solids remain in place and ongoing monitoring is not required.

### 6.2.1 Landfill Mass

Landfill solids volumes were calculated in the RI for pre-1980 solids (co-disposal practices ceased on August 11, 1980) and post-1980 solids (when waste disposal in Section 6 was restricted to municipal

refuse). The volume of pre-1980 landfill solids was estimated to be 3,200,000 cubic yards and the volume of post-1980 solids was approximately 8,900,000 cubic yards, for a total volume of approximately 12,100,000 cubic yards of landfill solids. The volume of total saturated solids and total unsaturated solids were calculated for the landfill mass. Approximately 220,000 cubic yards of the landfill solids were saturated, and the remainder were unsaturated. These calculations indicate that approximately 74 percent of the total solids at the LLSS were disposed of after 1980, and approximately 98 percent of the total solids volume is unsaturated.

The contamination within the landfill mass includes VOCs, SVOCs, metals, pesticides, PCBs, and radionuclides. The vertical and horizontal extent of landfill solids is shown on Figure 6-8. The figure shows pre-landfill and present-day topographic contours as well as isopach lines representing the thickness of refuse within the landfill's horizontal footprint. The former landfill occupies approximately 195 acres and is estimated to average 80 to 100 feet in thickness. Table 6-6 of the ROD presented a summary of chemicals detected in unsaturated solids within the landfill mass and their concentrations (EPA 1994).

The detection frequencies of the following VOCs exceeded 10 percent: 1,1-DCA; 1,1,1-TCA; 1,2-dichloroethane; 2-butanone; 4-methyl-2-pentanone; acetone; chloroform; methylene chloride; PCE; and TCE. Data from the RI generally showed the highest concentration of VOCs to be associated with unsaturated solids samples from within or below waste pits, thereby reflecting the impacts of residual waste pit liquid contamination. No samples exceeded established standards for TCLP VOCs.

Phthalates were the most commonly detected SVOC. There was no apparent areal distribution trend (that is, there were similar ranges of concentrations from areas with waste pits, medical waste, or no waste pits). However, there was a general vertical trend. In general, phthalate concentrations decreased with depth. Phthalates are common plasticizer chemicals, and the noted trend may have, therefore, reflected the increased use of plastics and plastic containers over time. The highest phthalate concentrations were detected in samples collected after 1980 (EPA 1994).

Phenol and polyaromatic hydrocarbons (PAH) were also frequently detected. As with the phthalate, there was no apparent areal distribution trend for phenol; however, there did not appear to be a general decrease in phenol concentrations with depth, as was observed for phthalates.

There were no distinct areal or vertical distribution trends for any of the metals (EPA 1994). The concentrations of the more toxic metals (such as arsenic, cadmium, chromium, and mercury) were generally below 50 milligrams per kilogram (mg/kg) except lead, which had a maximum detection of 1,410 mg/kg. No samples exceeded established standards for TCLP metals.

For radionuclides, the values measured were generally low and within the background concentrations established for soils as part of the OUs 4 and 5 RI (EPA 1994).

#### 6.2.2 Former Tire Pile Area

The FTPA, occupying approximately 54 acres, is immediately north of the main landfill mass and is shown on Figure 3-1. The measured depth to groundwater in this area generally ranges from approximately 10 to 15 feet. The tires that were formerly stockpiled in the area were shredded, a large portion sold to a local cement kiln as fuel, and the remainder was used as engineering filter bed material at LLSS. Waste pit disposal operations occurred in three general sections of the tire pile area. The three



waste pits that were under the tires were either excavated or covered with an earthen cover, as described in Section 5.3.

A geophysical investigation consisting of an electromagnetic survey was performed in conjunction with confirmatory trenching to estimate the number of buried drums in the FTPA. Nine confirmatory trenches were excavated in areas identified as anomalies by the geophysical investigation. Twelve corroded drums were encountered in four of the six anomalous areas. Data from the trenching efforts suggested that there were as many as 1,350 buried drums. The RI for OUs 2 and 3 estimated that approximately 19 percent (257 drums) of the total estimate of buried drums may have contained liquids (HSI and CDM 1993). Based on treatability study results, the RI also suggested that, on average, approximately 5 gallons of liquid may be present in each of the estimated 257 liquid-filled drums; this provides the basis for an estimated yield of a total liquid volume of no less than 1,300 gallons of liquid waste within the FTPA (HSI and CDM 1993).

Organic chemicals including VOCs, SVOCs, pesticides, PCBs, and inorganics including metals and cyanide were detected in subsurface solid samples in the FTPA. These chemicals are listed on Table 6-7 of the ROD (EPA 1994). The unsaturated solids are a source of groundwater contamination.

### 6.3 OU3: Landfill Gas

The primary sources of landfill gas contamination are subsurface liquids, saturated and unsaturated landfill solids, and leachate. As with other municipal solid waste landfills, methane gas and other gases are generated at the LLSS from the degradation of solids and chemical constituents present in the landfill mass. RI data were used to characterize the nature and extent of methane and other gases generated at the LLSS (HSI and CDM 1993). This section presents a summary of the RI sampling and conclusions, as described in the ROD, and more recent landfill gas collection, sampling, and treatment, as described in the first half 2020 SSR (EMSI and Parsons 2020).

Following the completion of the low permeability landfill cap in 1992, methane gas was regularly detected outside the landfill perimeter at monitoring points GMP-3, GMP-6A, GMP-7, and GMP-9 (shown on Figure 5-6). In addition, ambient (outdoor) air was sampled during the Phase I, Phase II, and Additional Site Characterization monitoring programs (EPA 1994). No site-related contaminants were found in the ambient air.

Frequently detected chemicals in landfill gas during the RI included 1,1,1-TCA, 1,1-DCA, carbon disulfide, chloroethane, methylene chloride, PCE, TCE, methane, and vinyl chloride. These compounds were detected most frequently in waste pit gas samples and samples from refuse located above the waste pits. Concentrations of the VOCs generally decreased with distance from the waste pits. The decrease in concentrations is attributed to the dilution of the volatiles carried within the methane generated from the refuse. Concentrations of contaminants in subsurface gas samples collected at the refuse surface, in areas with underlying waste pits, were approximately 1.5 to 10 times lower than concentrations in samples taken directly above the interface of the refuse and waste pit. Furthermore, concentrations of contaminants in samples collected at the refuse surface in areas without underlying waste pits were approximately 1 to 8 times lower than concentrations in samples taken from the same zone in areas with underlying waste pits (EPA 1994).

Headspace samples taken during the RI with Summa canisters<sup>24</sup> from monitoring wells in the waste pits provide an indication of the amount of chemicals volatilizing from the groundwater. Chemicals detected

in more than 50 percent of the samples include 1,2-dichloroethene, benzene, chloroethane, ethylbenzene, toluene, xylene, and vinyl chloride. These data provide information on the mixture and amount of chemicals historically emitted from groundwater and those that contribute to landfill gas volumes.

Volatile organics were also detected in gas samples taken outside the landfill mass but within the LLSS boundary during the RI. Soil gas samples taken from outside the landfill mass prior to 1994 indicated the presence of five chemicals: 1,1,1-TCA, benzene, ethylbenzene, toluene, and xylene. The compounds detected in these samples were also detected in gas samples taken from within the landfill mass or from gas probes adjacent to the landfill. Of the nine locations from which samples were analyzed, three samples showed consistent and positive detects—two on the north, and one on the southwest side of the landfill. Table 6-9 of the ROD presents the summary data for all the landfill gas samples (EPA 1994). Combustible gas was first detected in perimeter gas monitoring wells in August 1991. Four probes (GMP-3, GMP-6A, GMP-7, and GMP-9) were found to contain measurable levels of combustible gas. Table 6-8 of the ROD summarizes the methane data obtained from the perimeter gas monitoring wells.

In 1987, WMC conducted a gas recovery study for the Lowry Landfill and estimated gas generation rates were shown to be approximately 170 standard cubic feet per ton of solid waste per year (EPA 1994). The LLSS was estimated to contain approximately 5 million tons of solids. Therefore, the gas generation rate was estimated to be 1,600 standard cubic feet per minute (scfm) (EPA 1994). This generation rate was intended to be an "estimated maximum" and was expected to decrease with time.<sup>24</sup>

The WSDs continue to monitor landfill gas generation and for potential migration, as described in the landfill gas remedy LFG Compliance Monitoring Plan (EMSI 2018); data collection and evaluations are reported in the SSRs. The current LFG extraction, collection and treatment system consists of the following components: 64 vertical gas extraction wells, header and lateral piping, three automatic and nine manual condensate traps, two flares, and the GTEP. The Lowry LFG extraction and collection system is monitored monthly as part of the system O&M (EMSI and Parsons 2020). During the first six months of 2020, LLFS produced approximately 183 scfm of landfill gas (EMSI and Parsons 2020).

POC probe locations are shown in Figure 5-6. A biennial sampling event for VOCs was performed in June 2019. The data were validated and all results, with appropriate qualifiers, are presented in Appendix D-5 of the first half 2019 SSR (EMSI and Parsons 2019b). No POC subsurface gas performance standards were exceeded.

The POC probes were sampled quarterly for methane in the first half of 2020. All concentrations were below the methane performance standard of 5% by volume. The methane concentrations are summarized in Appendix D-6 of the first half 2020 SSR (EMSI and Parsons 2020).

#### 6.4 OU4: Soil

Soil contamination at the LLSS was investigated as part of the RI for OUs 4 and 5 (CDM 1993). Recent soil sampling or investigations have not been completed because the remedy is focused on contaminant

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<sup>24</sup> A Summa canister is a stainless steel container that has had the internal surfaces specially passivated using a "Summa" process. The degree of chemical inertness of a whole air sample container is crucial to minimizing reactions with the sample and maximizing recovery of target compounds from the container.

containment. The current nature and extent of contamination in OU4 is assumed to be similar to that summarized in the ROD (EPA 1994).

Four distinct areas of the LLSS (not including the landfill mass) were used for waste disposal and contribute to surface soil contamination. The areas are distinct either because of the type of waste disposed or the method of disposal. These areas are identified as: (1) the sewage sludge application/leachate injection area; (2) the sewage sludge application area; (3) the leachate spraying area; and (4) the FTPA. Figure 3-2 depicts the approximate boundaries of each area. For the purposes of this discussion, surface soil is defined as 0 to 12 inches in depth. Subsurface soil is defined as soil from a depth of 1 to 10 feet bgs. These depth intervals and the discussion of soil contamination in this section do not include the clean soil cover placed on the landfill mass or other remedy components, such as the SWRA or the FTPA.

For purposes of estimating the volume of soil in OU4, an aerial extent of approximately 103 acres (excluding the FTPA) and an average excavation depth of 15 feet was assumed. This depth was based on the detection of arsenic at 18,000 µg/kg at 6 feet bgs and the depth of the borrow area. The total volume of soil in OU4 was estimated to be approximately 2.5 million cubic yards (EPA 1994).

The contamination in surface soil at each waste disposal area is described in the following subsections. The four waste disposal areas are shown on Figure 3-2. The contaminants detected in subsurface soil is described as a whole and not differentiated between areas because of the limited number of samples and detected constituents.

#### 6.4.1 Sewage Sludge Application/Leachate Injection Area, Surface Soil

The sewage sludge application/leachate injection area is approximately 200 acres and is in the northern portion of Section 6 (Figure 3-2). Of the areas in which surface soils were sampled, this area contains the most organic chemicals. Thirty-eight organic chemicals were detected, although 68 percent of these were detected only once or twice. The PCB Aroclor-1260 was detected in eight samples within this area. This is the only area of the soil media in which Aroclor-1260 was detected in more than one sample. Although 2,3,7,8-Tetrachlorodibenzodioxin (TCDD) was not detected in samples from this area, nine other more highly chlorinated dioxins and furan isomers were detected in one sample out of two analyzed for these compounds.

Eighteen inorganic constituents were detected, with one constituent, selenium, detected only once in 11 samples. The inorganic chemicals that were detected were distributed throughout the area. The highest concentrations of inorganic constituents were detected in two adjacent sample locations near the unnamed creek channel. Eighteen samples were analyzed for radionuclides and four naturally-occurring isotopes<sup>25</sup> were detected in most of these samples.

The minimum and maximum detected and the mean concentrations of organic chemicals detected in surface soil samples taken from this area are presented on Table 6-10 of the ROD (EPA 1994). The mean was calculated by using one-half the detection limit as a place holder for samples without a value above the detection limit. Compared to the other areas identified under OU4, this area displayed the

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<sup>25</sup> A form of an element that has the same number of protons but a different number of neutrons in the nucleus, giving it a different atomic mass. For example, uranium has thirty-seven different isotopes, including uranium-235 and uranium-238.



maximum concentrations of organics. Specifically, the following three chemicals detected at concentrations exceeding 1,000 µg/kg: 4-chloroaniline, bis(2-ethylhexyl)phthalate, and Aroclor-1260.

Summary data for inorganic constituents are also presented on Table 6-10 of the ROD (EPA 1994). Maximum concentrations of inorganics for the LLSS, excluding manganese and aluminum, were detected within this area.

#### 6.4.2 Sewage Sludge Application Area, Surface Soil

The sewage sludge application area is approximately 40 acres on the eastern portion of the LLSS (Figure 3-2). Nine organic chemicals were detected in surface soil in this area. Five of these chemicals (benzoic acid, chloroform, 4,4'-dichlorodiphenyldichloroethane (DDD), di-n-octylphthalate, and toluene) were detected only once with methylene chloride and phenol detected twice. Only 4-chloroaniline and bis(2-ethylhexyl)phthalate were consistently detected in samples from this area. Background inorganic constituents, except selenium and thallium (no positive detections), were detected consistently throughout the area. No samples from this area were analyzed for radionuclides.

Summary data for organic chemicals in surface soil samples are presented on Table 6-11 of the ROD (EPA 1994). The most frequently detected chemicals, 4-chloroaniline and bis(2-ethylhexyl)phthalate had maximum concentrations of approximately 500 µg/kg. Table 6-11 of the ROD also presents inorganic summary data. The maximum concentration of manganese for the LLSS, 2,700,000 µg/kg, was detected in this area.

#### 6.4.3 Leachate Spraying Area, Surface Soil

The leachate spraying area is approximately 4 acres and located in the center of the LLSS, north of the landfill mass (Figure 3-2). Three organic chemicals, benzene, bis(2-ethylhexyl)phthalate, and methylene chloride were each detected once out of the seven samples in surface soil collected from this area. Chloroform was detected in one of two samples. Cyanide, selenium, silver, and thallium were not detected above the detection limit, and mercury was detected once. All other typical background inorganic constituents were detected consistently in samples from this area.

Summary data for organic chemicals in surface soil samples from the leachate spraying area are presented on Table 6-12 of the ROD (EPA 1994). Four organic chemicals (benzene, bis(2-ethylhexyl)phthalate, methylene, and chloroform) were detected only once each. The maximum concentration of these chemicals was 25 µg/kg or less, except for bis(2-ethylhexyl)phthalate, which had a maximum concentration of 215 µg/kg. Table 6-12 of the ROD also presented inorganic summary data. Concentrations of inorganic constituents in the leachate spraying area are generally lower than those detected in other soil areas.

#### 6.4.4 Former Tire Pile Area, Surface Soil

Thirty-four organic chemicals were positively detected in soil samples from the FTPA. The following pesticides were detected in more than one sample: alpha chlordane, dichlorodiphenyltrichloroethane (DDT), dieldrin, endrin aldehyde, gamma chlordane, and methoxychlor. Alpha chlordane was detected in more than half of the sample locations. In addition, nine PAHs were detected at one sample location along unnamed creek. Twelve inorganic constituents were detected at sample locations throughout the FTPA. Mercury was detected in two samples, selenium in one sample, and cadmium, cyanide, silver, and thallium were not detected above the detection limit in this area.

For this area, the minimum, maximum, and mean concentrations of organic chemicals in surface soil samples are presented on Table 6-13 of the ROD (EPA 1994). Although six pesticides were detected in more than one sample, none were detected at concentrations greater than 2.1 µg/kg. Table 6-13 of the ROD also presented inorganic summary data. The maximum historic concentration of aluminum for the LLSS, 7,860,000 µg/kg, was detected in the FTPA during the RI.

#### 6.4.5 Subsurface Soil

Organic chemicals, including VOCs, pesticides, and PCBs were detected infrequently in subsurface soil (soil from 1 to 10 feet bgs). The following organic chemicals were detected at a frequency greater than 10 percent: 2-butanone, 4-chloroaniline, acetone, methylene chloride, bis(2-ethylhexyl)phthalate, DDT, endrin, and Aroclor-1260. Subsurface samples from the sewage sludge application area, leachate spraying area, and FTPA were analyzed for radionuclides. Eight radionuclides (plutonium-239, potassium-40, strontium-90, thorium-228, -230, and -232, uranium-234, and uranium-238) were detected at a frequency of 100 percent. Lead-210 was detected at a frequency of 75 percent.

The data summary for subsurface soil is presented on Table 6-14 of the ROD (EPA 1994). No consistent distribution of organic chemical concentrations across the four distinct disposal areas could be determined with available sample data. In general, inorganic constituent concentrations decrease with depth. In the sewage sludge application area, zinc, lead, cadmium, nickel, and chromium exhibited lower concentrations in subsurface soil than in surface soil. In the leachate spraying area, concentrations of inorganics remained relatively unchanged throughout the soil profile. The maximum concentration of arsenic, 18,000 µg/kg, was detected in the leachate spraying area at the 4.5- to 6-foot interval. Two radionuclides, thorium-228 and potassium-40, were detected in background samples. Reported on-site concentrations for these radionuclides are comparable to the background concentrations.

### 6.5 OU5: Surface Water and Sediments

Surface water and sediment contamination at the LLSS was investigated as part of the RI for OUs 4 and 5 (CDM 1993). The SWRA was completed in 1992 to prevent contaminated groundwater from contacting surface water within the unnamed creek streambed. The SWRA extends between the NTES and the WTP access road and consists of permeable material beneath the streambed to channel groundwater flow to the NBBW and a clay cap to prevent contact between the surface water and groundwater.

This section summarizes the surface water and sediment investigations completed as part of the RI, as described in the ROD (EPA 1994), and includes more recent surface water data collected by the WSDs, as described in the North End Investigation Report (EMSI and CDM Smith 2020b).

#### 6.5.1 Surface Water within the Site Boundary

Historically, seeps were observed in locations along the banks of the unnamed creek near the center of Section 6. The sources of these seeps were believed to be the waste pits, groundwater discharge, and seepage from the toe of the landfill. The seeps contributed to perennial contaminated surface water flows in the unnamed creek. Prior to the SWRA, surface water would flow into the area previously occupied by Pond 3, which was located along the unnamed creek upstream of the NBBW (Figure 6-2). Previously, water that collected in Pond 3 would infiltrate through the bottom of the pond and into the subsurface (upgradient of the NBBW); it was then collected by the NBBW for treatment. During periods

of high precipitation, Pond 3 would overflow, which caused contaminated runoff to flow within the unnamed creek channel.

Prior to implementation of the SWRA and the NTES, numerous sampling events detected more than 20 organic chemicals in surface water in the unnamed creek—from the toe of the landfill to the area previously occupied by Pond 3. Within the unnamed creek drainage, between the area previously occupied by Pond 3 and the confluence of Murphy Creek, the detection of organic chemicals was infrequent and generally not reproducible because of dilution and low perennial flow. Inorganic constituents follow the same concentration pattern as organics; twice the number of inorganic constituents were detected (with a frequency over 50 percent) in Section 6 than beyond the area previously occupied by Pond 3.

The highest concentrations of organic chemicals that were detected in the unnamed creek prior to implementation of the SWRA and the NTES were found in samples collected in the surface drainage between the toe of the landfill and the area previously occupied by Pond 3. Significantly lower concentrations of organics were detected in samples downstream of the area previously occupied by Pond 3. Generally, concentrations of inorganic constituents were also highest in the unnamed creek between the toe of the landfill and the area previously occupied by Pond 3. Historical data are summarized on Table 6-15 of the ROD (EPA 1994).

Through implementation of the SWRA, measurable quantities of surface water flow within the unnamed creek have been eliminated. The SWRA collection system is designed to collect groundwater flow of up to 13 gallons per minute.

#### 6.5.2 Surface Water outside the Site Boundary

Creeks north of the site boundary interact with shallow groundwater in three ways: 1) a creek gains water from inflow of groundwater (gaining); 2) a creek loses water to groundwater by outflow to the groundwater system (losing); or 3) a creek loses and gains water from stormwater and/or snow melt and to the groundwater system depending on seasonality and stream reach. It is believed that Murphy Creek is both a gaining and losing stream at different reaches and at different times of the year in response to seasonal precipitation events, changes in ambient temperatures, and changes in vegetative growth along and adjacent to the creek channel (EMSI and CDM Smith 2020b).

Between 2006 and 2016, surface waters from Murphy Creek and ponds within or servicing the Murphy Creek golf course were sampled for COCs. Only 1,4-dioxane was detected above the groundwater performance standards. Sampling locations are identified as SWMC- and POND-series samples. The surface water sampling locations and results are shown on Figure 6-9.

In 2006, there were no detections of 1,4-dioxane in surface water from the main stem of Murphy Creek (east of the groundwater plume) between Yale Avenue and its confluence with the western branch of Murphy Creek (samples SW-5, SMWC-01, SWMC-02). This was confirmed in 2016 (EMSI and CDM Smith 2020b).

1,4-dioxane was detected in 2006 at concentrations above the groundwater performance standard at two sampling locations at the confluence of the main stem of Murphy Creek and the western branch of Murphy Creek (SWMC-03 and SWMC-04). These concentrations were believed to be caused by groundwater entering the stream channel (EMSI and CDM Smith 2020b). Further downstream (to the



north), concentrations decreased to estimated values of between 0.51 and 4.9 µg/L (SWMC-05, -06, and -07). In 2016, 1,4-dioxane concentrations at all sampling locations had decreased to less than the groundwater performance standard, except at SWMC-04 (3.1 µg/L).

Surface water sample SWMC-04 was collected from an unlined pond (golf course water hazard) that appears to be excavated into the shallow groundwater table. A shallow groundwater sample collected from nearby well MW142-WD in 2016 contained 1,4-dioxane at a similar concentration (3.3 µg/L) to that detected at SWMC-04. In contrast, the contribution (flux) of groundwater to surface water in Murphy Creek appeared to be low, based on the lower concentrations of 1,4-dioxane detected sample SWMC-03 (estimated at 0.46 µg/L), which is in adjacent Murphy Creek, and samples SWMC-05, -06, and 07 (estimated in the 0.5 to 0.6 g/L range), which are further downstream.

Surface water samples were collected from a lined storage pond between the main stem of Murphy Creek and the western branch of Murphy Creek. This storage pond receives reclaimed wastewater from Aurora's Sand Creek Wastewater Treatment Plant. Pond water is used to irrigate the Murphy Creek Golf Course. Samples labeled JPOND-01/SWMC-09 were collected from its influent pipe and samples labeled JPOND-02/SWMC-08 were collected from its outlet structure (Figure 6-9). In 2006, water entering and leaving the pond contained 1,4-dioxane at estimated concentrations of 1.9 µg/L and 1.6 µg/L, respectively. Because the pond water is applied to the Murphy Creek golf course for turf irrigation, the potential exists for this water to impact North End groundwater quality (EMSI and CDM Smith 2020b). 1,4-dioxane was not detected in either pond water location in 2015 and was not detected at JPOND-01/SWMC-09 and detected at an estimated concentration of 0.17 µg/L at JPOND-02/SWMC-08 in 2016.

### 6.5.3 Sediments

Construction of the SWRA eliminated the off-site transport of surface water and suspended sediments in the unnamed creek. As part of the SWRA, a soil cap was constructed in the on-site portion of the unnamed creek channel. The potential sources of sediment contamination in the unnamed creek were the same as those identified for surface water. Sediments within the unnamed creek in Section 6 are now covered by the SWRA soil cap.

Prior to the implementation of the SWRA, at least 15 organic chemicals were detected in sediments within the on-site unnamed creek channel. Few organic chemicals were detected in sediments downstream of the area previously occupied by Pond 3. Inorganic constituents were detected above background levels throughout the creek channel as well as beyond the confluence of the unnamed creek and Murphy Creek.

The SWRA soil cap covers approximately 320,000 square feet (EPA 1994). This area includes the location of former Ponds 3 and 4 (Pond 4 was located directly west of the existing treatment plant, shown on Figure 6-2). The volume of contaminated sediments that were left in place and covered by SWRA soil cap has not been estimated. The volume of sediments in the unnamed creek segment of Section 31 is estimated to be 23,700 cubic yards.

The ROD included separate descriptions of the sediment contamination in Section 6 and Section 31. These descriptions are summarized below.

*Section 6 Sediments.* Prior to implementation of the SWRA, elevated concentrations of organic chemicals were detected in the sediments of the unnamed creek. Specifically, these chemicals were

found in samples collected from the portion of the creek channel that is within the FTPA. For example, 1,1,1-TCA, toluene, and total xylenes were detected at maximum concentrations greater than 100 mg/kg. Significantly lower organic concentrations were detected upstream of this area, in the general vicinity of the toe of the landfill. All sediments in Section 6 were covered as part of the SWRA.

Elevated concentrations of barium, chromium, and lead were detected in sediment samples from within the creek channel in the FTPA, near the waste pits on the east side of the former creek. Historical data for sediments in Section 6 are summarized on Table 6-16 of the ROD (EPA 1994).

*Section 31 Sediments.* Samples collected downstream of the NBBW in Section 31 exhibited inconsistent detections of organic chemicals. The area downstream of the NBBW in Section 31 can be divided into two smaller geographical segments to more easily discuss contaminants detected:

- From the southern boundary of Section 31 to the confluence with Murphy Creek; and
- From the confluence with Murphy Creek to northern boundary of Section 31.

Fifteen organic chemicals were detected in the segment from the southern boundary of Section 31 to the confluence with Murphy Creek. Eleven of these chemicals were detected only once. Of those chemicals detected more than once, bis(2-ethylhexyl)phthalate had the highest detection frequency at 50 percent. PCBs, toluene, and acetone had detection frequencies between 30 and 40 percent. The maximum concentrations of these organic compounds were below 1 mg/kg except for 2,4-dinitrophenol, which was detected once at 2.7 mg/kg out of 11 samples.

Seventeen inorganic constituents (out of 19 analyzed) were detected within the segment from the southern boundary of Section 31 to the confluence with Murphy Creek. Two (cyanide and tin) were detected only once. The remaining fifteen compounds had detection frequencies greater than 40 percent. Two inorganic chemicals not detected in these sediment samples were antimony and silver. Average concentrations of most inorganic constituents were approximately the same as those calculated for Section 6. However, average concentrations of barium, chromium, mercury, and lead were half to one order of magnitude lower than those calculated for Section 6.

Five organic compounds were detected in the segment from the confluence with Murphy Creek to the northern boundary of Section 31. Three of these were detected only once. Bis(2-ethylhexyl)phthalate and octochlorodibenzodioxin were detected more than once (three and two detections, respectively).

Eighteen inorganic constituents (out of 19 constituents analyzed) were in the segment from the confluence with Murphy Creek to the northern boundary of Section 31. Four constituents (silver, iron, antimony, and tin) were detected only once. The remaining constituents had detection frequencies between 20 and 88 percent. Average concentrations of most inorganic constituents were approximately the same as those calculated for Section 6. However, average concentrations of arsenic, barium, chromium, manganese, mercury, and lead were half to one order of magnitude lower than those concentrations calculated for Section 6.

## 6.6 OU6: Deep Groundwater

The deep groundwater system at the LLSS includes the water-bearing zones beneath the Dawson Aquifer, which includes the upper and lower Denver aquifers. Several deep monitoring wells were installed at the LLSS. Historical sampling conducted as part of the RI included deep monitoring wells B-504 and C-702Q2. B-504 and C-702Q2 were abandoned in 1996, after the completion of the RI. B-504

was replaced with B-504A. These historical wells were screened from 105 to 125 feet and 162 to 172 feet bgs, respectively. It was determined that well B-504 had been drilled through a waste pit and the contaminant concentrations detected in this well were determined by EPA and EPA's contractor CH2M Hill to be a result of drag-down during drilling and not representative of conditions in deeper groundwater (HLA 1992). B-504 was replaced with a new well (B-504A) that was offset from B-504 by 40-feet to the south and 19 feet to the east to avoid the waste pit that B-504 was installed in and the surface water removal action activities immediately to the northwest of former well B-504. Groundwater sampling at B-504A after installation indicated that deep groundwater in this area was unimpacted and remains unimpacted with maximum concentrations of all compounds of concern below respective performance standards (EMSI and Parsons 2020).

During the RI monitoring, well cluster C-702 was installed approximately 1,000 feet north and downgradient from B-504 and wells C-702P2 and C-702P3 were installed with screens placed in the B-sand to confirm that deep groundwater in this area was unimpacted. The C-702P2 well screen was placed in the lower part of the B-sand and the C-702P3 well screen was placed 20 feet higher, near the top of the B-sand. C-702P3 and C-702P2 are co-located, are installed close together in the same sand lens, and thus both wells represent very similar groundwater conditions, so groundwater samples were collected from C-702P3 while only water level data was collected from C-702P2 (HLA 1992). Groundwater sampling at C-702P3 during the RI indicated that deep groundwater in this area was unimpacted at that time except for one reported detection of acetone, a common laboratory contaminant, at 24 µg/L.

Monitoring wells were also installed as part of the C-702 well cluster below the B-sand (C-702Q2 and C-702P1) in deep groundwater and down to the lignite layer (C-702Q1) at approximately 219 feet bgs. Groundwater sampling during the RI at these deep wells indicate that deep groundwater in this area was unimpacted at that time. Groundwater samples continue to be collected periodically at C-702Q1 and C-702P3 to monitor for potential vertical migration. Analytical data collected during the most recent groundwater sampling event in 2018 that included these wells indicated that maximum concentrations for all compounds for each well were less than their respective performance standards and deep groundwater in this area remains unimpacted (EMSI and Parsons 2020).

During the RI, contaminants detected within the deep groundwater monitoring wells included organics, radionuclides, and trace metals; however, the reported detections of these chemicals were primarily from well B-504 which EPA and CH2M Hill concluded was likely introduced during well construction and/or drilling. RI sampling results indicated that the average concentrations of organics in deep groundwater monitoring wells B-504 and C702-Q2 were substantially lower than the average concentrations of organics in shallow groundwater (EPA 1994). Deep groundwater quality continues to be monitored and reported in the SSRs.

During the last five years, only 1,4-dioxane and nitrate were detected above the performance standard in the unweathered bedrock wells associated with the sand channel north of the NBBW. During the 2018 synoptic groundwater sampling event, 1,4-dioxane and nitrate were detected above the standards in 6 of the 62 unweathered bedrock wells, all 6 are located near the NBBW (MW113-UD, B-326-UD, BW-PZ-1LC, MW-EW-1LCRA, MW-EW-2LCR, and B-316-UD). The unweathered wells sampled during the 2018 and 2019 are shown on Figure 6-10. 1,4-dioxane has not been detected above the performance



standard of 0.9 µg/L in the unweathered wells below approximately 50 feet bgs north of the compliance boundary (EMSI and CDM Smith 2020b).

Although they are not compliance wells (because they are not located on the POC), vertical migration wells B-504A, B-712-LD, C-702P3, and GW-113 are sampled periodically as part of the GWMP to compare concentrations in deeper groundwater to the groundwater performance standards (Figure 6-10). Upper Denver wells B-504A, C-702P3, and GW-113 are sampled every five years and unweathered Dawson well B-712-LD is sampled every two years. The four wells have not been sampled since 2018 and the most recent results and statistical analyses were reported in the second half 2018 SSR (EMSI and Parsons 2019b). The maximum concentrations of all compounds detected in wells B-504A, C-702P3 and GW-113 in 2018 were less than the groundwater performance standards. The historical maximum concentrations of all compounds detected in well B-712-LD were also less than the performance standards except for one detection of 1,4-dioxane at 0.95 µg/L in 2007. The seven subsequent samples obtained from this well were all non-detected for 1,4-dioxane.

Two private domestic wells (Private Well 1 and Private Well 2), located along East Jewell Avenue, have been sampled annually each spring (second quarter) since 2006 for 1,4-dioxane. There are no other active supply wells (individually- or municipally-owned) within or immediately adjacent to the 1,4-dioxane plume. All other private or municipal supply wells located within or immediately adjacent to the 1,4-dioxane plume have been decommissioned and cannot be sampled. The TCHD, with support from the WSDs, will continue sampling the two active supply wells for 1,4-dioxane using the most recent, applicable analytical methods.

The two private domestic wells were last sampled in June 2020. The two private domestic wells are screened in unweathered bedrock at depths of 375 to 600 feet bgs. Sampling of these wells was intended to provide assurances to the well owners that are proximal to the shallow groundwater plume that their drinking water does not contain any site compounds of concern above acceptable levels. No 1,4-dioxane has ever been detected in private water supply wells within or adjacent to the 1,4-dioxane plume (EMSI and CDM Smith 2020b). In addition to 1,4-dioxane, the June 2020 sampling effort included analyses for VOCs, nitrate, and major anions and cations. These analytes were either not detected or detected below the Lowry groundwater performance standards.

## 6.7 Properties of Detected Chemicals

The chemicals detected in the groundwater, soil, surface water, sediment, and landfill solids, liquids and gas include VOCs, SVOCs, metals, pesticides, PCBs, and radionuclides. Those chemicals identified as COCs for each medium are listed on Table 3-2. Basic information on the historical use, fate and transport, and health effects of these compounds is presented in this section.

### 6.7.1 Volatile Organic Compounds

VOCs are organic chemicals that have a high vapor pressure (low boiling point) and low water solubility. VOCs evaporate under normal atmospheric conditions. Most of the COCs identified at the LLSS are VOCs.

VOCs have been used extensively in the United States since the 1940s. VOCs are common components or additives in many industrial, commercial, and household products, including gasoline, carpets, paints, glues, cleaners, manufacturing processes, dry cleaning, and degreasing of equipment and home septic systems (USGS 2020). VOCs in surface water volatilize (evaporate) into air. VOCs in subsurface liquid

can volatilize into soil pore spaces as soil vapor, dissolve into groundwater, or migrate through the subsurface vertically or horizontally as NAPLs. Volatilized VOCs can accumulate in indoor air, causing potential risks to receptors within the building or even explosion hazards at high concentrations. Once in the groundwater, many VOCs are persistent. Some highly soluble VOCs, such as the gasoline additive MTBE, move with the groundwater, whereas other VOCs, like carbon tetrachloride, are slowed when they adhere to organic carbon in the aquifer solids. Some VOCs are degraded by bacteria in the aquifer, but others resist degradation and can be transported very long distances (USGS 2020).

VOCs are typically released into the subsurface as either aqueous-phase or nonaqueous phase liquids (NAPLs). At LLSS, VOCs were contained within the landfill refuse and subsurface liquids. Waste disposal, such as that at LLSS, would typically cause a mixture of fuel hydrocarbons or sludges and chlorinated solvents which, depending on the relative proportion of each compound group, may be more or less dense than water. Contaminant sources generally consist of chlorinated solvents present as mobile NAPL (NAPL occurring at sufficiently high saturations to drain under the influence of gravity into a well) and residual NAPL (NAPL occurring at immobile, residual saturations that are unable to drain into a well by gravity). The greatest mass of contaminant is typically associated with these NAPL source areas, not with the dissolved phase contamination (USGS 2020).

When released at or near the surface, NAPLs move downward under the force of gravity and tend to follow preferential pathways such as along the surface of sloping fine-grained layers or through fractures in soil or rock. Large NAPL releases can extend laterally from the release point. DNAPL releases can sink through groundwater by following preferential flow paths. An LNAPL layer will move up and down with fluctuations of the groundwater table, resulting in a smear zone above and below the water table. As water moves through NAPL areas (recharge in the vadose zone or groundwater flow in an aquifer), the more soluble constituents partition into the water to generate a plume of dissolved contamination and the more volatile contaminants partition to the vapor phase. After surface releases have stopped, NAPLs remaining in the subsurface tend to “weather” over time as volatile and soluble components are depleted from NAPL surfaces. Even considering this “weathering” effect, subsurface NAPLs continue to be a source of contaminants to groundwater for a very long time.

NAPL does not occupy the entire pore space; rather, water, NAPL, and often gas/vapor phases are present together in a multiphase configuration controlled primarily by capillary forces<sup>26</sup> and gravity (buoyancy) (EPA 2012a). The continuous NAPL zones may spread, depending on the available volume of NAPL and the soil and liquid properties controlling NAPL mobility (e.g., multiphase permeability and capillary relationships). When a release stops, NAPL zones will eventually reach a dynamic equilibrium and thereafter remain relatively immobile. The formation of continuous-phase NAPL depends on a release volume large enough to occupy the unsaturated pore space; otherwise all of the separate-phase liquid may be trapped as immobile and discontinuous residual NAPL in the unsaturated or saturated zones without collecting as a continuous-phase NAPL zone.

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<sup>26</sup> Capillary action refers to the movement of liquids upward toward the surface through narrow spaces in the soil. The movement is due to the combination of surface tension and adhesive forces of the liquid, similar to the way paint is drawn up between the hairs of a paintbrush.

Once in the subsurface, the movement of VOCs in groundwater and soil gas is controlled by diffusion, advection, biodegradation, sorption, and mixing. These transport processes are described below (EPA 2012a).

- Diffusion refers to the process whereby molecules move from an area of higher concentration to an area of lower concentration. Diffusion will lead to chemical migration away from the highest concentration source area (i.e., NAPL or a dissolved plume). Diffusion can also lead to chemical migration into buildings directly through a dirt floor or crawl space or through cracks, pores, and other openings in the building slab and foundation. The migration of volatile chemicals into indoor air is called vapor intrusion.
- Advection refers to the movement of liquids or gases in response to pressure or hydraulic gradients. NAPLs and dissolved-phase contaminants move with groundwater in response to hydraulic forces and vapor-phase contaminants migrate from areas of greater pressure to areas of lower pressure.
- Biodegradation refers to the process by which chemical compounds are altered through the biological activity of microorganisms in the subsurface. Biodegradation can occur through aerobic or anerobic processes<sup>27</sup>.
- Sorption refers to the partitioning of chemicals into the solid phase. VOCs tend to preferentially adsorb onto soil organic matter. In soils with high organic carbon content, movement of organic compounds is inhibited.
- Mixing refers to the blending of soil gas with ambient air or of dissolved-phase contaminants with uncontaminated groundwater.

The most prevalent VOCs detected at the LLSS include chlorinated solvents; petroleum hydrocarbons (including benzene, toluene, ethylbenzene, and xylenes); and 1,4-dioxane. These compounds are described in more detail below.

#### *Chlorinated Solvents*

Chlorinated solvents are chemical compounds that contain chlorine. Examples of chlorinated solvents at the LLSS include 1,1,1-TCA, PCE, TCE, and 1,1-DCA. Chlorinated solvents are used for a wide variety of commercial and industrial purposes, including degreasers, cleaning solutions, paint thinners, pesticides, resins, glues, and industrial cleaning solutions, such as dry cleaning. The chlorine structure gives them the ability to absorb organic materials and efficiently dissolve fats and greases.

Chlorinated solvents like PCE and TCE are denser than water and form DNAPLs that sink through the groundwater column. Chlorinated solvents can biodegrade in the subsurface under anaerobic conditions. Biodegradation of chlorinated solvents can produce toxic degradation products, such as 1,1-DCA and vinyl chloride.

#### *Petroleum Hydrocarbons*

Petroleum hydrocarbons are chemical compounds made up of hydrogen and carbon that are constituents of petroleum and various refined products of petroleum, including automotive gasoline, diesel fuel, and lubricating oils (EPA 2012a). Benzene, toluene, ethylbenzene, and xylenes (commonly referred to as “BTEX” compounds) are common constituents of petroleum hydrocarbons.

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<sup>27</sup> Aerobic means that the process requires oxygen. Anaerobic means the process does not require oxygen.



Petroleum hydrocarbons and their constituents biodegrade readily under aerobic (oxygenated) environmental conditions. Biodegradation of petroleum constituents usually produces carbon dioxide, water, and sometimes methane or other simple hydrocarbons. The aerobic biodegradability of petroleum hydrocarbons can generally limit the potential for subsurface migration of vapors. BTEX compounds have low water solubility, are lighter than water, and form LNAPLs that “float” on the groundwater surface. They volatilize quickly when exposed to air.

#### *1,4-Dioxane*

1,4-dioxane has been used in a variety of industrial applications but mainly for the stabilization of the chlorinated solvent 1,1,1-TCA (ATSDR 2012). Solvent stabilizers are often required to mitigate harmful reactions between solvents and metals, which form acids as the solvent decomposes. 1,4-dioxane is also a chemical byproduct of several chemical processes and may be used in the production of plastics and polymers, inks, paints, and coatings, adhesives, automotive fluids, and consumer products such as cleaners, detergents, shampoo, and cosmetics. 1,4-dioxane is likely to be present in wastewater discharges to publicly owned treatment works (POTW) due to the widespread use of 1,4-dioxane in consumer products (New York State Pollution Prevention Institute [NYSPP] 2017).

1,4-dioxane has high solubility in water, low vapor pressure, and minimal sorption to organic carbon. Therefore, it is most likely found in the environment as dissolved in groundwater or surface water. Infiltration of 1,4-dioxane through soil and into groundwater occurs with minimal inhibition because of its miscibility in water and low potential for adsorption to organic carbon. Once dissolved in water, 1,4-dioxane tends to stay dissolved and its low volatilization potential limits vapor intrusion. A 1,4-dioxane plume may appear to move more slowly than the average groundwater velocity as a result of diffusion into and back out of low-permeability zones (a process called matrix diffusion). Matrix diffusion within porous media may contribute to the long-term persistence of 1,4-dioxane groundwater plumes (Interstate Technology Regulatory Council [ITRC] 2020). Although chemical characteristics of 1,4-dioxane suggest greater mobility than chlorinated solvents that are released at the same locations, the empirical data suggest that the plumes are likely to be co-located (Adamson et al. 2014). However, in some cases (Mohr et al. 2020), 1,4-dioxane plumes can extend well beyond the organic co-contaminant plumes. These circumstances may be due to oxygen-poor (anaerobic) aquifer conditions that are conducive to biodegradation of the co-contaminants but not of 1,4-dioxane. 1,4-dioxane can biodegrade under aerobic conditions but degradation rates may be inhibited by co-occurring chlorinated solvents, low oxygen concentrations, low concentrations of 1,4-dioxane, and the lack of suitable co-substrate (for cometabolic degradation) (ITRC 2020).

The major exposure pathway related to environmental releases of 1,4-dioxane is ingestion of contaminated drinking water. Other exposure pathways are minor and include incidental ingestion of impacted soil, dermal contact, and inhalation. While 1,4-dioxane could reach aquatic and terrestrial biota, the limited data available suggest that bioaccumulation<sup>28</sup> potential is negligible at concentrations typically associated with impacted groundwater (EPA 2018).

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<sup>28</sup> Bioaccumulation is the concentration of a chemical within the body of a living organism. Bioaccumulation occurs when the organism takes in the chemical at a faster rate than it is released.

### 6.7.2 Semi-volatile Organic Compounds

SVOCs are organic compounds that volatilize slowly at standard temperature and pressure. SVOCs are a subgroup of VOCs that typically have higher molecular weights and boiling point temperatures than VOCs, which means they are not as volatile as VOCs. SVOCs present at the LLSS include 1,2-dichlorobenzene, 1,2,4-trichlorobenzene, 2-methylnaphthalene, phenol, pentachlorophenol, and naphthalene. Like VOCs, SVOCs can occur in the subsurface as vapors (soil gas), dissolved in groundwater, or as NAPLs. SVOCs include polycyclic aromatic hydrocarbons (PAHs), phenols, and phthalates.

PAHs are formed during the incomplete burning of coal, oil and gas, garbage, or other organic substances like tobacco or charbroiled meat. Some PAHs are manufactured and are found in coal tar, crude oil, creosote, and roofing tar and a few are used in medicines or to make dyes, plastics, and pesticides (ATSDR 1996). PAHs are generally biodegradable in soil systems. Lower molecular weight PAH components are more water soluble than higher molecular weight PAHs. Readily mobilized compounds, such as naphthalene, phenanthrene, and anthracene, are slightly water-soluble. Persistent PAHs, such as chrysene and benzo(a)pyrene, possess even lower water solubilities (Department of Defense Environmental Technology Transfer Committee 1994).

Phenols are organic compounds that are byproducts of petroleum refining, tanning and textile, dye, and resin manufacturing. Phenol has also been used for medicine as a slimicide, antiseptic, and disinfectant. Phenol is soluble in water and biodegrades under both aerobic and anaerobic conditions. People can be exposed to phenols through inhalation, ingestion, and dermal contact.

Phthalates are used in numerous industrial and consumer products, primarily as plasticizers in PVC products. Phthalates are oily liquids at room temperature and have moderate volatility from moist soil surfaces and water. They have low to moderate mobility in soil and water systems. They are expected to be readily biodegradable, but the rate of degradation is considered slow. In general, phthalates are not persistent in soil and do not bioaccumulate in receptors.

### 6.7.3 Metals

Metals include elements with a metallic luster and are found on and beneath the earth's surface, such as iron, manganese, lead, cadmium, zinc, nickel, gold, and mercury. Metals and metalloids are electropositive elements that occur in all ecosystems, although natural concentrations vary according to local geology. While some metals are essential as nutrients, all metals can be toxic at some level. Some metals are toxic in minute amounts.

Metals are mostly immobile in soil and adsorption and precipitation processes will inhibit the movement of metals from soil to groundwater. However, some metals (or metal compounds) dissolve in water or volatilize. Changes in soil environmental conditions over time, such as the degradation of the organic waste, changes in pH, redox potential, or soil composition due to various remediation processes or natural weathering may enhance metal mobility (EPA 1992c). Metals, unlike organic chemicals, cannot be degraded. However, some metals, such as chromium, arsenic, and mercury, can be transformed to other oxidation states in soil, reducing their mobility and toxicity. Metal speciation<sup>29</sup> greatly determines

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<sup>29</sup> Speciation refers to the occurrence of a metal in a variety of chemical forms. These forms may include free metal ions, metal complexes dissolved in solution and sorbed on solid surfaces, and metal species that have been coprecipitated in major metal solids or that occur in their own solids.

the behavior and toxicity of metals in the environment. The speciation of a metal affects not only its toxicity but also its volatilization, photolysis, sorption, atmospheric deposition, acid/base equilibria, polymerization, complexation, electron-transfer reactions, solubility and precipitation equilibria, microbial transformations, and diffusivity (Bodek et al. 1988).

#### 6.7.4 Pesticides

The term pesticide is applied to thousands of different, specific chemical-end products. Pesticides include insecticides, fungicides, herbicides, acaricides, nematocides, and rodenticides. Pesticide products contain both "active" and "inert" ingredients. An "active ingredient" prevents, destroys, repels, or mitigates a pest, or is a plant regulator, defoliant, desiccant, or nitrogen stabilizer. All other ingredients are called "inert ingredients" by federal law. They are important for product performance and usability. However, "inert" does not mean non-toxic and all inert ingredients must be approved by EPA before they can be included in a pesticide. EPA regulates pesticides under the Federal Insecticide, Fungicide, and Rodenticide Act.

Active ingredients are the chemicals in a pesticide product that act to control the pests. Active ingredients must be identified by name on the pesticide product's label together with its percentage by weight. There are several categories of active ingredients:

- Conventional, which are all ingredients other than biological pesticides and antimicrobial pesticides.
- Antimicrobial, which are substances or mixtures of substances used to destroy or suppress the growth of harmful microorganisms whether bacteria, viruses, or fungi on inanimate objects and surfaces.
- Biopesticides, which are types of ingredients derived from certain natural materials.

The pesticides detected at the LLSS include alpha chlordane, DDT, dieldrin, endrin aldehyde, gamma chlordane, and methoxychlor. Many of these pesticides are no longer manufactured or used because of their health effects. Typically, pesticides are applied to the ground surface to kill insects, weeds, or rodents. The fate and transport of the chemical may vary but in general pesticides persist in the soil. For example, dieldrin sticks to soil and may stay in place unchanged for many years. It degrades in soil or water very slowly and does not easily wash off with water. Dieldrin does not dissolve in water very well and is therefore not found in water at high concentrations, but can attach to soil and sediments at the bottom of lakes, ponds, and streams. Dieldrin evaporates slowly from surface water or soil and can be taken up from the soil by plants and stored in leaves and roots. It can travel large distances by attaching to dust particles that are dispersed by the wind.

#### 6.7.5 Polychlorinated Biphenyls

PCBs are a group of man-made organic chemicals consisting of carbon, hydrogen, and chlorine atoms. The number of chlorine atoms and their location in a PCB molecule determine many of its physical and chemical properties. PCBs belong to a broad family of man-made organic chemicals known as chlorinated hydrocarbons and includes up to 209 variations or congeners with different physical and chemical characteristics. They have a range of toxicity and vary in consistency from thin, light-colored liquids to yellow or black waxy solids. Information about PCBs can be found on EPA's website (<https://www.epa.gov/pcbs/learn-about-polychlorinated-biphenyls-pcbs>).



PCBs were domestically manufactured from 1929 until manufacturing was banned in 1979. Due to their non-flammability, chemical stability, high boiling point and electrical insulating properties, PCBs were used in hundreds of industrial and commercial applications. Although no longer commercially produced in the United States, PCBs may be present in products and materials produced before the 1979 PCB ban. Products that may contain PCBs include:

- Transformers and capacitors
- Electrical equipment including voltage regulators, switches, re-closers, bushings, and electromagnets
- Oil used in motors and hydraulic systems
- Old electrical devices or appliances containing PCB capacitors
- Fluorescent light ballasts
- Cable insulation
- Thermal insulation material including fiberglass, felt, foam, and cork
- Adhesives and tapes
- Oil-based paint
- Caulking
- Plastics
- Carbonless copy paper
- Floor finish

PCBs alone are not usually very mobile in subsurface soils or water; however, they are typically found in oils associated with electrical transformers or gas pipelines or sorbed to soil particles, which may transport the PCBs by wind or water erosion (Department of Defense Environmental Technology Transfer Committee 1994). PCBs do not readily break down once in the environment. They can remain for long periods cycling between air, water and soil. PCBs can be carried long distances and have been found in snow and sea water in areas far from where they were released into the environment. As a consequence, they are found all over the world. In general, the lighter the form of PCB, the further it can be transported from the source of contamination.

PCBs can accumulate in the leaves and above-ground parts of plants and food crops. They are also taken up into the bodies of small organisms and fish. As a result, people who ingest fish may be exposed to PCBs that have bioaccumulated in the fish they are ingesting.

PCBs were commonly used as mixtures called aroclors. The most common aroclors are Aroclor-1254, Aroclor-1260, and Aroclor-1242. Aroclors were produced from approximately 1930 to 1979.

#### 6.7.6 Radionuclides

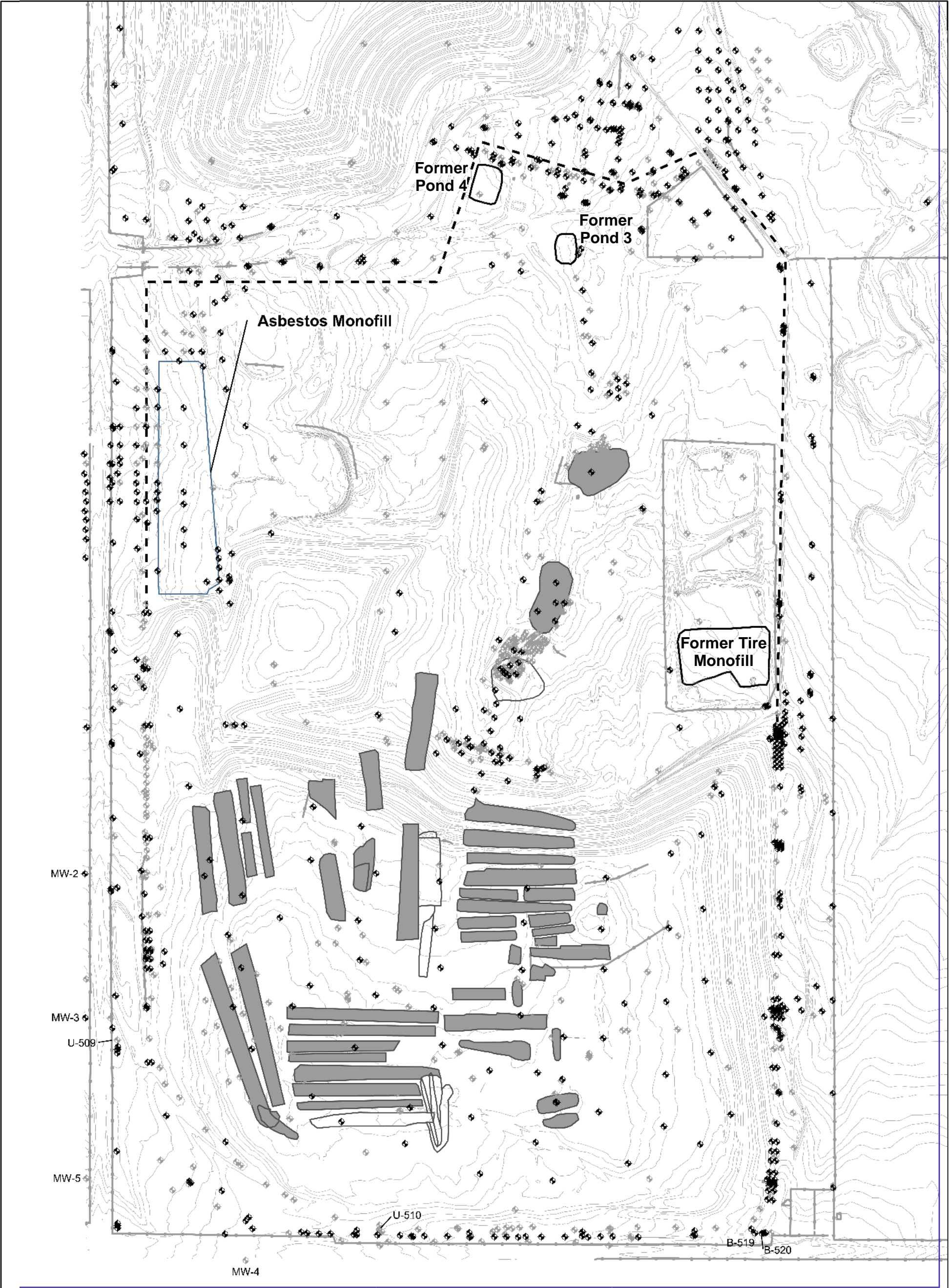
Radioactive forms of elements are called radionuclides. Some occur naturally in the environment, while others are man-made, either deliberately or as byproducts of nuclear reactions. Every radionuclide emits radiation at its own specific rate, which is measured in terms of half-life. Radioactive half-life is the time required for half of the radioactive atoms present to decay. Radioactive decay is when a radioisotope transforms into another radioisotope; this process emits radiation in some form. Some radionuclides have half-lives of mere seconds, but others have half-lives of millions of years. Radionuclides have properties similar to heavy metals. Like metals, radionuclides are typically

nonvolatile and less soluble in water than other contaminants. EPA's website provides additional information on radionuclides (<https://www.epa.gov/radiation/radionuclides>).

Draft for Public Review







Legend

- ◆ Active Wells
- ◆ Abandoned Wells

BKGD-2WD

BKGD-2UD

BKGD-3WD

N

0 250 500 Feet

1 inch = 500 feet

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado



**Figure 6-2**  
**Waste Pit and**  
**Well Locations**

Source: Figure 6-2 (Parsons GIS 2020)





Legend

-  Domain of 3D Data Visualization and Analysis
-  Monitoring Wells used in 2018 Groundwater Visualization



Approximate Scale: 1 inch = 1,700 feet

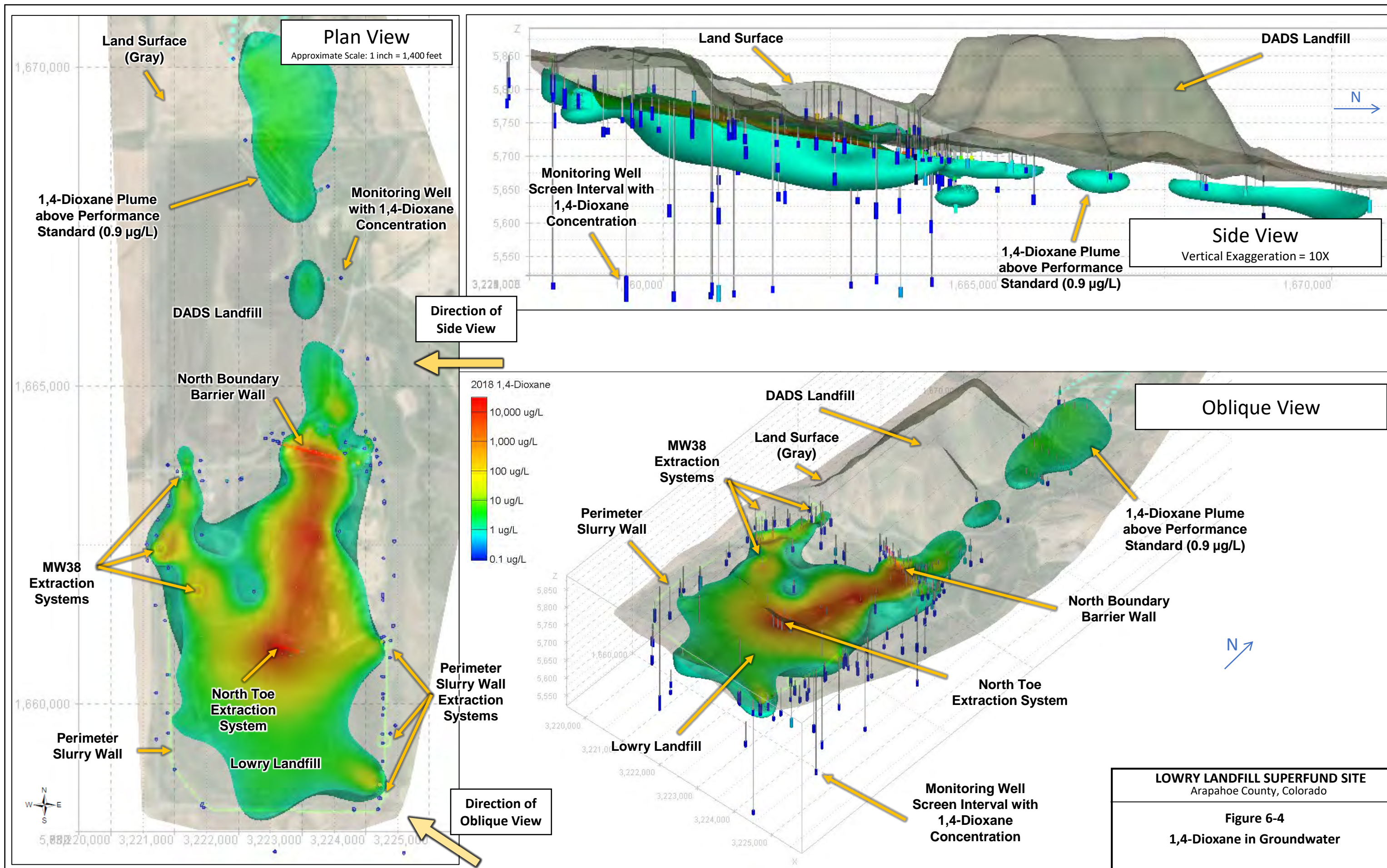
Note: Domain is the krig boundary of the project data but is not the complete extent of the data included in visualizations.

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

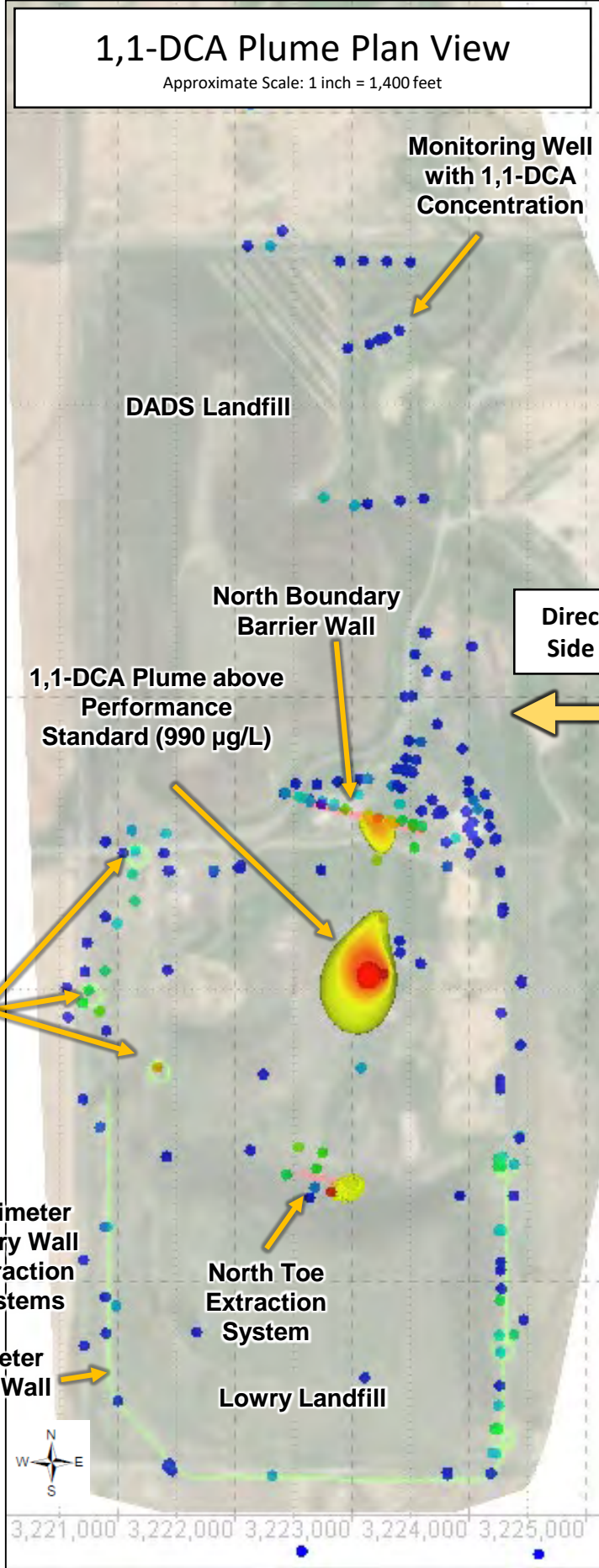
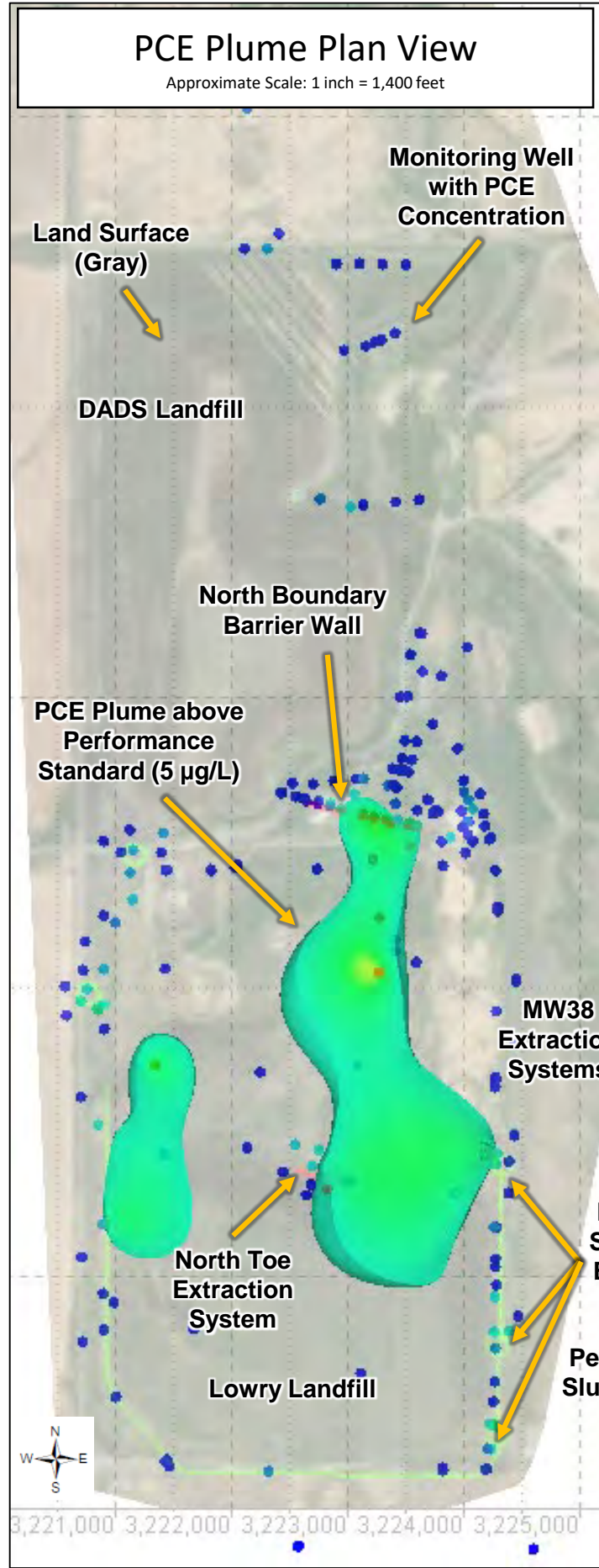
**Figure 6-3**  
**Monitoring Well Network for 2018 Synoptic Sampling Event**

Base Layer Source: Esri, DigitalGlobe, GeoEye, Earthstar Geographics, CNES/Airbus DS, USDA, USGS, AeroGRID, IGN, and the GIS User Community

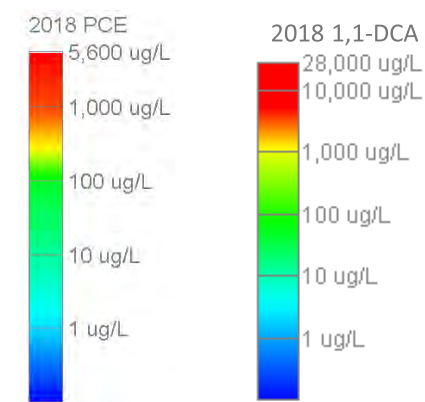
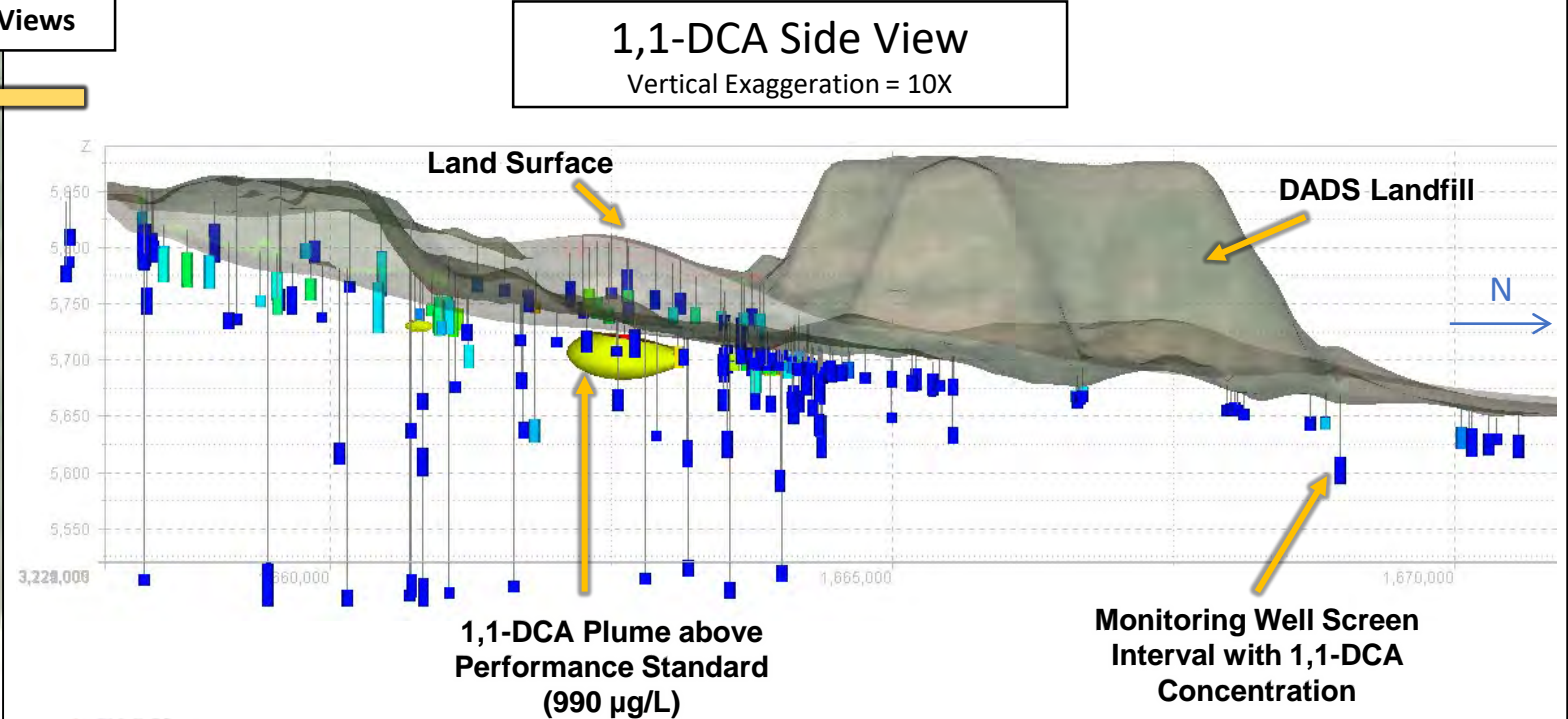
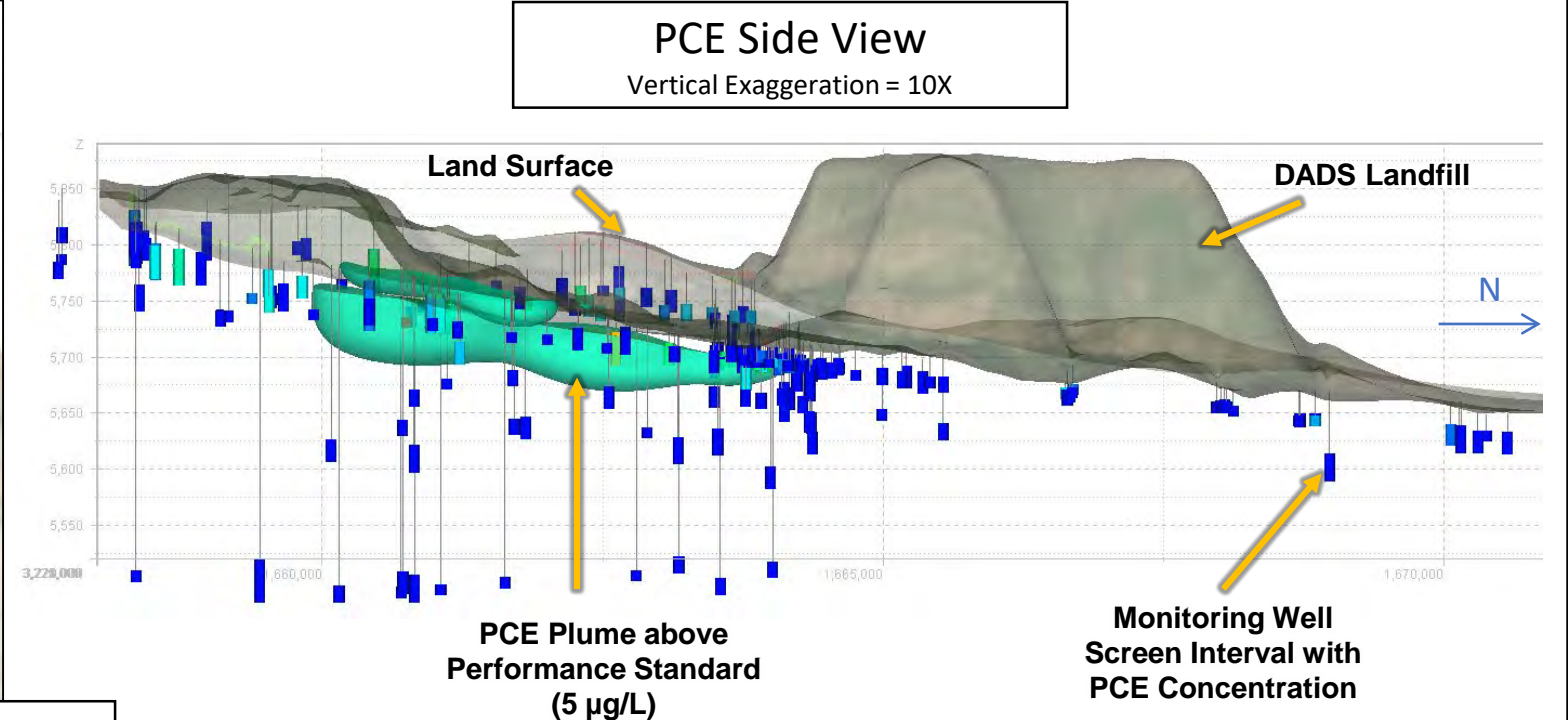








Direction of Side Views



Notes:

µg/L microgram per liter

1,1-DCA 1,1-Dichloroethane

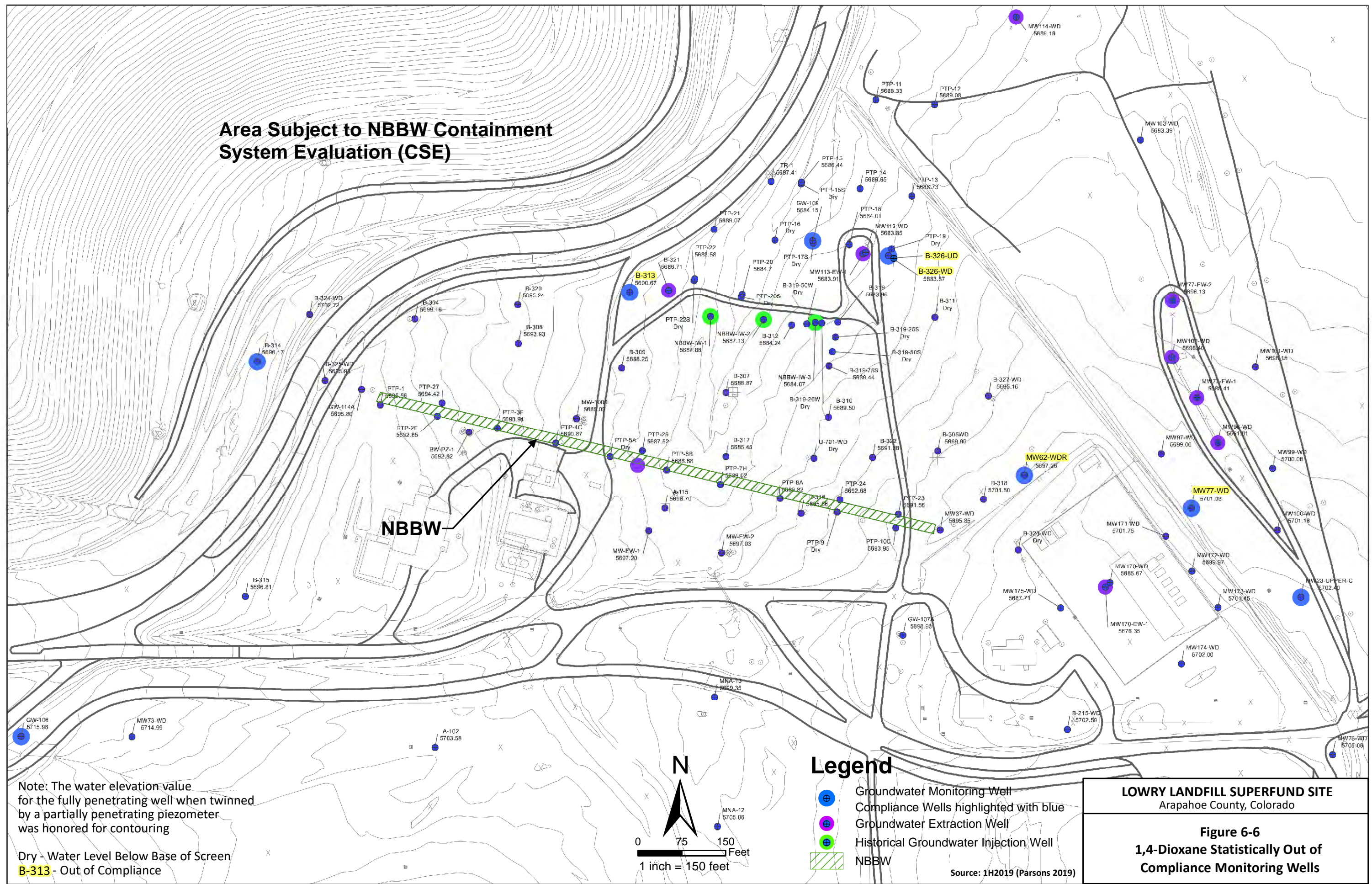
PCE Tetrachloroethene

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

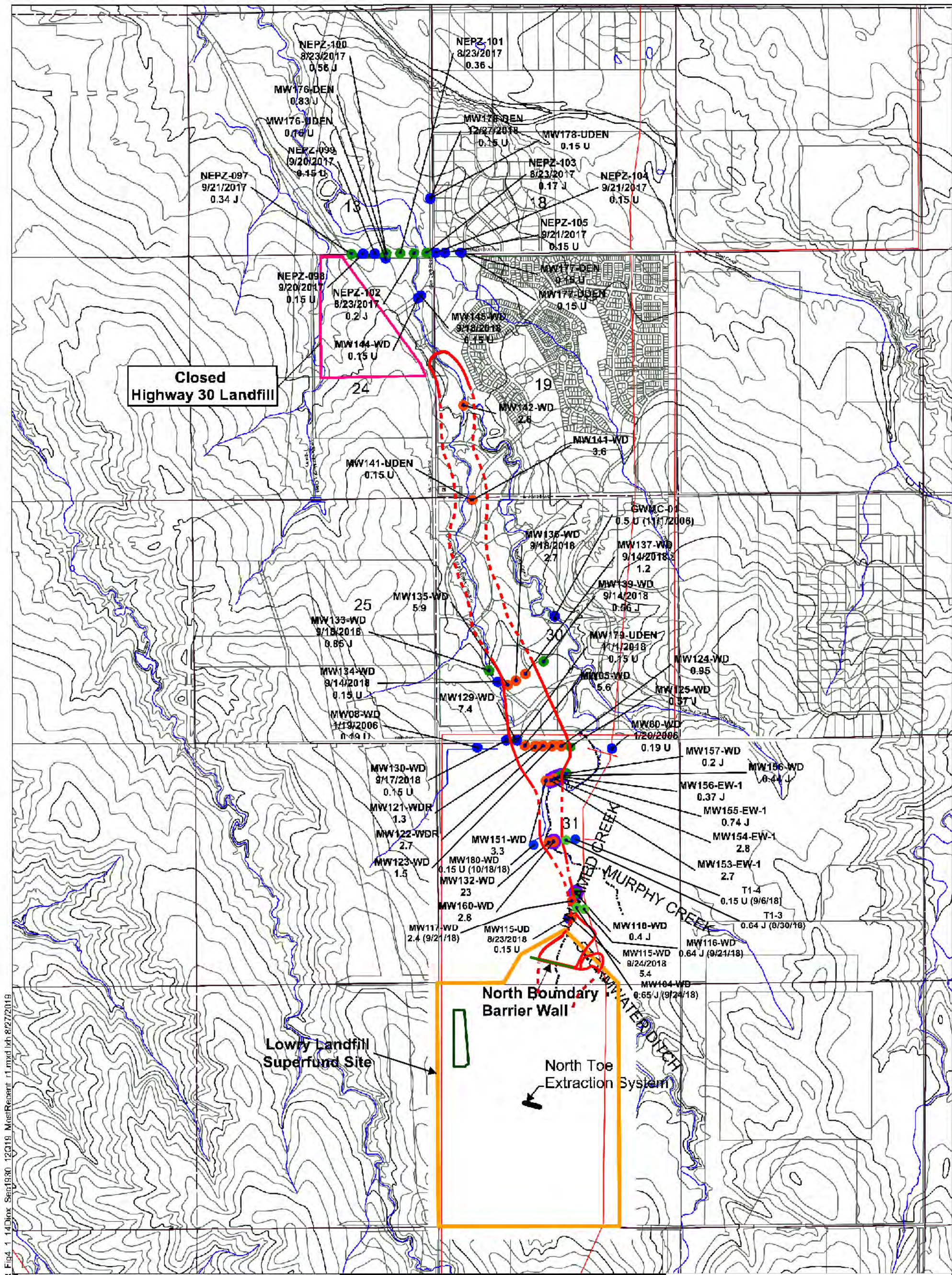
**Figure 6-5**  
**PCE and 1,1-DCA in Groundwater**



# Area Subject to NBBW Containment System Evaluation (CSE)







S:\ESMajProj\Lowry\NFI\Steven\Fig6-7.mxd 8/27/2019 MostRecent: r1.mxd lkh 8/27/2019

**Legend**

- DETECTED 14X > 0.9 ug/L PERFORMANCE STANDARD
- DETECTED 14X <= 0.9 ug/L PERFORMANCE STANDARD
- NO 1,4-Dioxane (14X) DETECTED
- EXTRACTION WELL
- DOMESTIC WELL LOCATION
- Approximate Limits 1,4-Dioxane concentration greater than site's performance standard of 0.9 ug/L in groundwater (dashed where inferred)
- J = ESTIMATED VALUE
- U = UNDETECTED
- \*Sample dates were all in 2019 unless otherwise posted

N

0 2,000 Feet

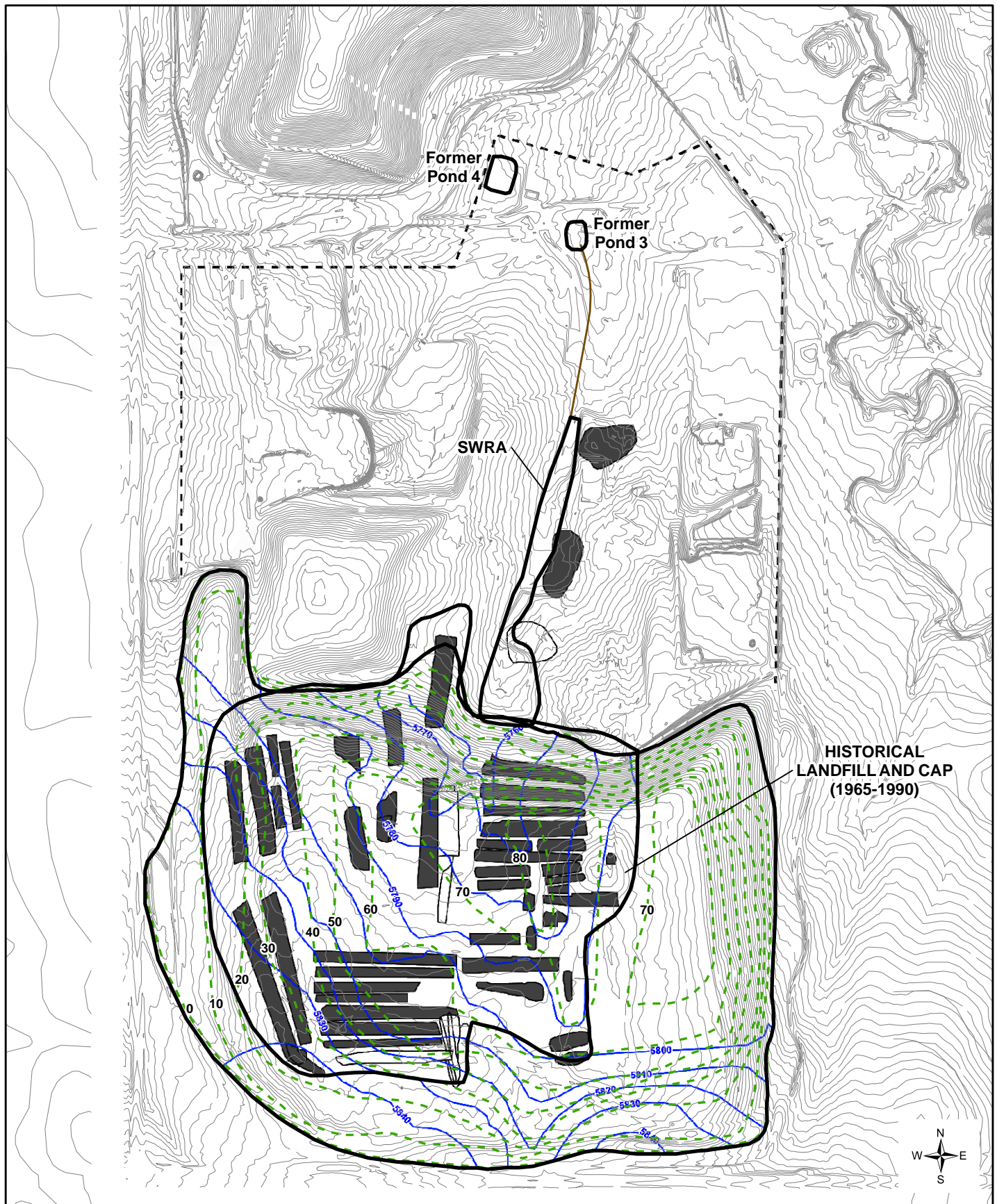
1 inch = 2,000 feet

Source: Figure 4.1 North End Investigation (EMSI 2020)

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**FIGURE 6-7**  
**SECTIONS 13, 18, 19, 24, 30 AND 31**  
**1,4-DIOXANE 2019 RESULTS\***



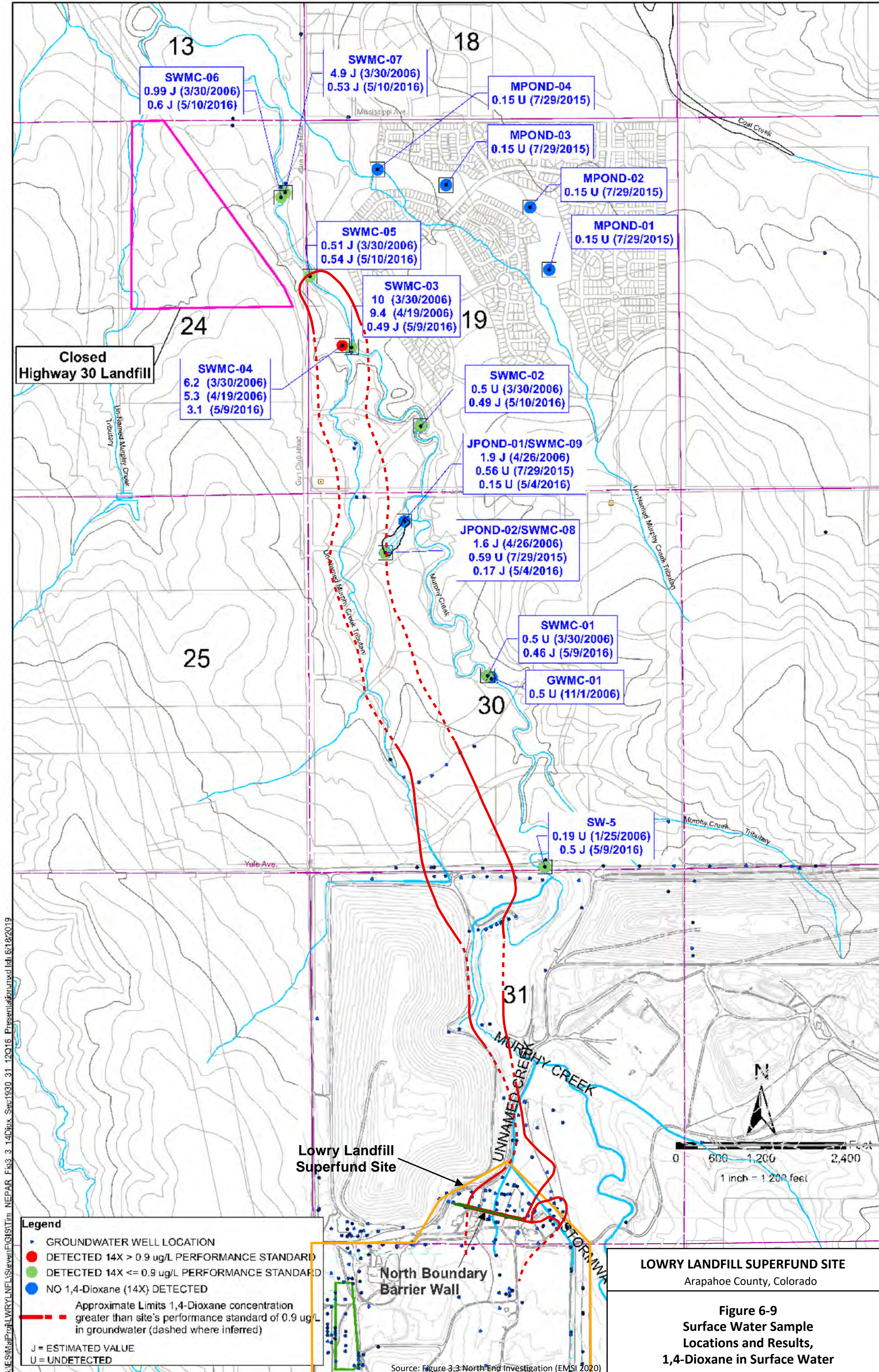


- Pre-landfill topography contour interval, 10 foot
- Post-Landfill topography contour interval, 2 foot
- - - Isopach line for total refuse above pre-landfill topography, 10 foot interval

**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 6-8**  
**Historical Landfill and Cap**









## 7.0 Contaminant Fate and Transport

The sources of contamination at the LLSS, as described in Section 6.0, include waste pit liquids, saturated refuse, landfill solids, sewage sludge, and leachate injection/spraying. These sources have and will continue to transmit contaminants to environmental media such as soil, groundwater, surface water, and landfill gas. These environmental media may act as secondary sources for distributing contamination throughout the environment.

Sampling of soil, groundwater, surface water, sediment, and landfill gas was conducted during the pre-Phase I, the Phase I and Phase II RIs, and the Additional Site Characterization efforts to assess media interactions and their potential as secondary sources of contamination. Interactions were evaluated as part of each OU RI Report. The 1994 ROD discussed only the significant pathways of migration, based on their contribution to site risk. The discussion of contaminant migration from the ROD is presented in this section with updated data and conclusions from recent investigations and the effects of the remedy components.

The significant pathways of migration identified in the ROD include

- Subsurface liquids to shallow groundwater
- Subsurface liquids and shallow groundwater to surface water and sediments
- Volatiles from subsurface liquids to landfill gas
- Landfill solids to landfill gas to the atmosphere
- Leachate from landfill solids to shallow groundwater
- Contaminated surface water to shallow groundwater
- Shallow groundwater to deep groundwater

An additional migration pathway has been added to those identified in the ROD: the migration of contamination in shallow groundwater from within the site boundaries to groundwater outside of the POC. The main migration pathways are shown on Illustrations 3-1 and 5-1.

The site's long-term remedy components were designed and implemented to prevent migration of contamination beyond the vertical and horizontal limits of the POC. The remedy components are described in Section 5.0 and shown on Figure 3-3. The POCs for landfill gas and groundwater were identified in the ROD and shown on Figure 3-3. If performance standards are not met during implementation and operation, the remedy requires appropriate contingency measures to be implemented. The site's remedy is currently in the long-term O&M stage. The effect of the remedy components on the fate and transport of the contamination is described for each migration pathway in the following sections.

### 7.1 Subsurface Liquids to Shallow Groundwater

Contaminants from the waste pits migrated into both the weathered and unweathered Dawson shallow groundwater system. Migration within the shallow groundwater occurs primarily in a horizontal direction with limited vertical migration, as described in Section 4.2. In certain areas within the site boundary, waste pits and shallow groundwater have no hydraulic separation. As a result, the waste pit liquids and shallow groundwater co-mingle. Illustrations 3-1 (a) and (b) shows the waste pit liquids and the migration of contaminants into shallow groundwater.



Although contaminants in the waste pit liquids are similar to contaminants in the shallow groundwater, individual comparisons of analytical results between waste pit well points and adjacent shallow groundwater monitoring wells indicate variable trends (EPA 1994). The differences in contaminant occurrence and concentrations between the well points and adjacent monitoring wells could result from one or more of the following conditions:

1. Variability in geology
2. Lack of contaminant migration, or variability in the rate, volume, and pattern of contaminant migration from the waste pits
3. Location of a waste pit in relation to the water table
4. The influence of other waste pits on the monitoring wells
5. The presence and possible migration of multiple liquid phases in the waste pits (NAPLs)
6. Contaminant migration from the waste pit along pathways not encountered by the adjacent monitoring wells

Components of the remedy do not prevent the migration of contaminants from the waste pit liquids to shallow groundwater within the site boundaries; however, the remedy does include components to minimize this migration. The former landfill is covered by 4 to 12 feet of compacted clay and soil. This landfill cover reduces infiltration of rain and snow into the soil, which minimizes the penetration of stormwater into the landfill mass and waste pits and, in turn, minimizes the migration of contaminated liquid to shallow groundwater. The landfill cover is routinely monitored for any depressions that may form due to settlement that would cause rainwater to pond. In addition, the perimeter slurry wall was constructed along the east, south, and west boundaries of the landfill mass and waste pits to minimize the flow of clean shallow groundwater onto the site, thereby minimizing contact between shallow groundwater and subsurface liquid and thus minimize further contaminant migration.

Subsurface sand channels have been identified at the LLSS. Subsurface fluid flow (including shallow groundwater and subsurface waste liquids) is preferentially occurring in these sand channels. Extraction features, such as the MW38 sand channel extraction system, the NTES, and the NBBW (and associated extraction wells), have been placed along these sand channels to remove and treat contaminated groundwater. The WSDs are conducting detailed supplemental evaluations of the effectiveness of the NBBW containment system as part of the CSE and Optimization Study.

## 7.2 Subsurface Liquids and Shallow Groundwater to Surface Water and Sediments

Data collected during Phase I and Phase II investigations (before the SWRA was completed) confirmed that the shallow groundwater and subsurface liquids located within or just below the landfill mass flowed to the north and discharged to the unnamed creek. Available data also support the conclusion that the shallow groundwater and subsurface liquids in the FTPA were discharged to the surface water through seeps located along the banks of the unnamed creek (EPA 1994). These groundwater discharges contributed to the base flow within the unnamed creek. For the area north of the former tire piles, available data support the conclusion that the shallow groundwater system was recharged through surface water infiltration.

The majority of the organic compounds that were detected in the shallow groundwater and subsurface liquids were also detected in surface water, and at a similar frequency of detection (EPA 1994). A similar correlation was observed between shallow groundwater and sediments, although the contaminants

were typically detected less frequently in sediments. Concentrations of organics detected in shallow groundwater were typically higher than in the surface water or the sediments.

Based on the correlation between contaminant levels in sediments and their location with respect to waste pits, contaminants from the waste pits migrated through the groundwater and had discharged via seeps to surface water in the unnamed creek (EPA 1994).

Implementation of the SWRA isolated the groundwater, surface water, and sediments and prevents off-site migration of contaminated surface water. The SWRA includes a low-permeability cover that prevents groundwater from contacting surface water within the unnamed creek drainage. Beneath the clay cover, the SWRA includes a layer of more permeable material to channel shallow groundwater towards the NBBW for capture. In addition, the NTES was installed at the base of the landfill mass to collect subsurface liquids and NAPLs emanating from the waste pits and landfill refuse before they can contact surface water or sediments.

### 7.3 Volatiles from Subsurface Liquids to Landfill Gas

Analyses have shown that both the waste pit and refuse gas samples contained similar organic compounds. Because these two types of samples were collected at various elevations above the waste pits, the results indicated that: (1) within the refuse, waste pit vapors and waste pit gases were highly mobile and widely dispersed in the subsurface within the site boundaries; and (2) that the refuse served as a source for gas generation (EPA 1994). Landfill gas—made up of methane, carbon dioxide, nitrogen and other gases—is created naturally by the biological decomposition of organic matter in landfills under low-oxygen conditions. In addition, similar VOCs were detected in the landfill gas and in the source area shallow groundwater, which indicated interactions between the media.

The LLSS remedy includes extraction, collection and treatment of the landfill gas, which prevents the migration of the gas beyond the POC, minimizes fugitive emissions to the atmosphere, and minimizes the interaction of the landfill gas with shallow groundwater. The landfill gas extraction, collection, and treatment system removes approximately 5,000 tons of methane annually (EMSI and Parsons 2019c). The on-site GTEP, constructed in 2008, uses landfill gas to fuel four internal combustion engines that generate electricity for a local utility company.

### 7.4 Landfill Solids to Landfill Gas to Atmosphere

Significant pathways of migration between the landfill solids, landfill gas, and the atmosphere are as follows (EPA 1994):

- Gas produced within the landfill mass migrates primarily by advective flow in the subsurface and into the atmosphere.
- The highest contaminant concentrations and the greatest number of contaminants at the perimeter tend to occur closest to the landfill margin.
- The composition and concentrations of VOCs detected in perimeter areas are consistent with gas compositions within the landfill mass.
- Soil gas VOC concentrations in the FTPA are consistent with VOC concentrations within the waste pits; (landfill) gas contamination by VOCs in the FTPA is characterized by localized sources.

As described in the previous section, the landfill gas is extracted and treated on site. The WSDs monitor landfill gas concentrations at the POC to provide detection of any releases of landfill gas from the site.



The POC is shown on Figure 5-6. According to the latest SSR, the landfill gas system continues to be effective at collecting the generated gas and preventing migration of the contaminated gas beyond the POC (EMSI and Parsons 2019c).

### 7.5 Contaminated Surface Water to Shallow Groundwater

Currently, the migration of contaminants in surface water to shallow groundwater on the LLSS is controlled by the SWRA and the landfill and FTPA covers. Before remedial actions were implemented, the migration of contamination was not controlled and seepage to the unnamed creek transported contaminants to the sediments and surface water. The potential contribution of contamination from sediments and surface water to the shallow groundwater depended on the amount of precipitation runoff and recharge that occurred within the unnamed creek during that period.

Prior to implementation of the SWRA, surface water was observed to infiltrate into the subsurface through the bed of the unnamed creek (EPA 1994). A comparison of surface water data (from the area previously occupied by Pond 3) to groundwater data (from wells located along the unnamed creek north of the FTPA) indicated recharge from contaminated surface water potentially impacted groundwater in the FTPA. Other sources, including subsurface liquids, also had a significant impact on groundwater quality in this area of the site.

Completion of the SWRA eliminated potential recharge to the shallow groundwater system underlying the unnamed creek. In addition, the covers constructed over the landfill mass and FTPA minimize the infiltration of water through the contaminated material and into the shallow groundwater.

### 7.6 Shallow Groundwater to Deep Groundwater

The groundwater monitoring program includes monitoring of groundwater in the unweathered Dawson and upper Denver inside the POC to detect potential vertical migration. Groundwater monitoring to detect potential vertical migration is performed beneath and immediately downgradient of the source area. The overall objective of monitoring deeper bedrock units inside of the POC is to monitor the potential for vertical migration by detecting occurrences of deeper contamination or changes in concentrations, if any, at depth (EMSI and Parsons 2018).

Monitoring for potential vertical migration is separate and distinct from compliance monitoring and from the monitoring performed to demonstrate the effectiveness of the various remedy components. The purpose of monitoring for potential vertical migration is to allow for ongoing assessment of the well network and sampling frequency used for the deeper compliance monitoring wells at the site. Water quality data obtained from the interior deeper monitoring wells is used to identify necessary modifications to the compliance monitoring network or sampling frequencies for the deeper units to detect possible occurrences of contamination above performance standards in the deeper units that may be migrating towards the horizontal or vertical POC.

In general, the presence of a downward component to the hydraulic gradient would indicate a potential for downward migration of contamination from the source area into the underlying formations; however, this downward component is wholly or partially offset by the lower permeability of the deeper bedrock units compared to that of the alluvium and weathered bedrock (EMSI and Parsons 2018). Contaminant concentrations above the performance standards are detected mainly in shallow groundwater within the alluvial deposits and weathered portion of the Dawson Formation bedrock. Isolated detections of contaminants in groundwater samples obtained from the deeper bedrock units at

the site (unweathered Dawson, upper Denver, and lignite) have been reported, some of which were above performance standards. However, the majority of these detections could not be confirmed by subsequent sampling and may be the result of inadequate well construction or cross contamination during sampling (EMSI and Parsons 2018).

Hydraulic gradient data collected as part of the RI indicate that downward vertical gradients exist between the shallow and deep groundwater. Historical chemical analyses from the deep groundwater indicate the presence of low levels of organic contamination near monitoring wells B-504 and C-702Q2 during the RI (HLA 1992). Therefore, a potential exists for contaminated shallow groundwater to migrate to the deep groundwater (EPA 1994), contributing to the need for ongoing monitoring of deeper wells even in the absence of detections. The maximum concentrations of all compounds detected in wells B-504A, C-702P3 and GW-113 in 2018 were less than the groundwater performance standards. The historical maximum concentrations of all compounds detected in well B-712-LD were also less than the performance standards except for one detection of 1,4-dioxane at 0.95 µg/L in 2007. The seven subsequent samples obtained from this well were all non-detected for 1,4-dioxane.

The vertical extent of 1,4-dioxane detected above the performance standard of 0.9 µg/L indicates that groundwater contamination occurs primarily in the weathered Dawson formation, with limited migration into the unweathered bedrock formations (Figure 6-4). 1,4-dioxane was chosen as an indicator chemical because of its widespread distribution across the site and its chemical properties (described in Section 6.7.1). 1,4-dioxane is miscible, which means that it fully dissolves in water, forming a homogenous solution. 1,4-dioxane is not expected to adsorb to suspended solids and sediment if released into water and has the potential to migrate farther in groundwater than co-occurring chlorinated solvents such as 1,1,1-TCA or other VOCs because of its high solubility and low affinity for sorption to soil organic matter (Mohr 2001). Therefore, 1,4-dioxane is an appropriate indicator chemical to represent the furthest extent of dissolved-phase groundwater contamination.

Vertical migration and the presence of groundwater contamination in the deep groundwater was investigated for the North End Area. The North End investigation report concluded that there was no significant connection between the shallow and deep groundwater units north of the LLSS. This conclusion was based on the following (EMSI and CDM Smith 2020b):

- The presence of low permeability sediments (approximately 20 to 30 feet thick) at or beneath the contact of the weathered/unweathered lithology within the North End Area.
- The difference in the hydraulic conductivities estimated for the weathered and unweathered lithologies.
- The absence of 1,4-dioxane detected in the deep unweathered wells located within the North End Area.
- The differences in the nitrate concentrations detected in shallow and deep groundwater monitoring wells and the lack of nitrate detected in the private water supply wells (which are screened at 375 and 600 feet bgs).

## 7.7 Shallow Groundwater to Groundwater Outside Point of Compliance

The site's remedy was designed to minimize the off-site migration of contaminated shallow groundwater by collecting the contaminated water at the barrier wall and pumping it to the groundwater treatment plant. Four remedy components have been implemented to maintain



containment of contaminated groundwater at the site including: the perimeter slurry wall, NTES, NBBW, and maintenance of an inward hydraulic gradient into the MW38 channel. The specific design objectives vary among the different containment features, but each component provides a mechanism for hydraulic control that prevents downgradient transport of contaminants via groundwater flow. However, concentrations of COCs above the performance standards have been detected outside the POC from the time these features were installed to present. Groundwater COCs have been detected above the performance standards outside the perimeter slurry wall, just north of the POC at the northern extent of the MW38 sand channel, and downgradient of the NBBW.

Contamination outside the POC may be a result of (1) contaminant migration that occurred before the remedy components were constructed; (2) emplacement of contamination in areas outside the current POC (sewage sludge land farming or reinjection of treated water); or (3) migration of contamination after remedy construction. These pathways are discussed in this section. A focused and detailed CSE and Optimization Study is currently being conducted to utilize all information collected to date (including additional efforts undertaken for the evaluation) to characterize whether ongoing migration is occurring and to identify data gaps. If issues with containment are determined or suspected, the appropriate actions will be taken.

The perimeter slurry wall limits groundwater inflow to and outflow from the landfill mass around its west, south and east sides. When designed and constructed, the perimeter slurry wall was located to encompass source areas but also placed to avoid existing utilities and roadways. Shallow groundwater containing concentrations of contaminants above the performance standards had migrated outside the footprint of the slurry wall before the wall was constructed. Consequently, the slurry wall did not encompass the entire known extent of contaminated groundwater. Contingency measures, in the form of extraction wells and air sparging, were implemented to address contamination outside the slurry wall. The perimeter slurry wall extraction systems are shown on Figure 3-3.

The MW38 channel hydraulic controls limit downgradient migration of contaminants by maintaining an inward hydraulic gradient. The MW38 channel is a natural feature that results in convergent flow into the higher hydraulic conductivity sand deposits in this feature, thereby restricting off-site flow to the west (figure 5-11). The MW38 channel may have extended to the north, under the DADS landfill in Section 31; however, much of the permeable deposits may have been excavated when the landfill liner was emplaced. Convergent flow into the channel has been enhanced by groundwater extraction from the within channel, which has created an inward hydraulic gradient surrounding the channel. Chloroform and 1,4-dioxane concentrations in monitoring well MW38-830N-230E exceed their groundwater performance standards. This well is located outside the POC at the north end of the MW38 channel. However, groundwater extraction from the MW38 channel is conducted at two locations, one of which is approximately 200 ft north of well MW38-830N-230E. Therefore, groundwater at this compliance monitoring well is hydraulically contained within, and removed from, the sand channel (EMSI and Parsons 2019c) and additional characterization beneath DADS is not necessary. In addition, contaminant concentrations at compliance well MW38-830N-230E have steadily declined since 2005. 1,4-dioxane concentrations at this well have declined by 98.9% as of 2020 when the 1,4-dioxane concentration at this well was 2.8 µg/L (EMSI and Parsons 2020). Contaminant concentrations have also declined over time at wells in the vicinity of the MW38 channel (e.g., MW38-1028N-256E and MW38-170S-140W) (EMSI and Parsons 2020). One monitoring well in the eastern part of the NBBW system (MW62-WDR) contains concentrations of nitrate above the performance standard.

This well is in an area where sewage sludge was historically land farmed to cultivate and enhance microbial degradation of the organic matter. As described in Section 6.1, the compliance boundary straddles the land farming area. Groundwater extraction from the North End wells further downgradient prevents potential migration of nitrate contamination.

The NBBW prevents further downgradient flow beyond the zone of influence of its pumping system. However, before the NBBW was constructed, contaminated groundwater flowed beyond the POC in this area. Furthermore, treated water was reinjected north of the NBBW before the WTP was modified to remove 1,4-dioxane. As described in Section 5.0, the WTP initially was designed with a focus on removal of VOCs but did not remove 1,4-dioxane, nitrate, or other constituents. Until 2000, the treated water containing 1,4-dioxane was injected downgradient of the NBBW. These activities resulted in the presence of contamination outside the POC.

Residual contamination downgradient of the NBBW likely exists not only in the more permeable coarser-grained sand deposits but also in the less permeable finer-grained sands, silt and clay deposits within the alluvium along unnamed creek and in the unweathered bedrock (EMSI and Parsons 2018). Release of contamination from these finer grained deposits will be controlled primarily by matrix diffusion. That is, contaminants are initially present in higher permeability zones such as sands or gravels and then diffuse into adjacent low permeability zones, most commonly silts or clays. After the main source of contamination is removed, the remaining contamination slowly diffuses from lower permeability zones back out into the groundwater in the more permeable units. Matrix diffusion is a relatively slow process that can continue to contribute contamination to the groundwater for many years. Groundwater performance standards may not be achieved because of residual contamination even if the remedy is functioning as intended. Further evaluation of the residual contamination and the effectiveness of the NBBW at capturing groundwater contamination will be conducted as part of the NBBW CSE and Optimization Study.

Investigations to characterize the lateral and vertical limits of 1,4-dioxane in groundwater downgradient of the NBBW have been ongoing since 2000. Comprehensive sampling programs were conducted in 2006, 2007, and 2018 to evaluate the 1,4-dioxane concentrations downgradient of the NBBW, including off site to the north in Sections 31, 30, 24, and 19. Results of these investigations showed that 1,4-dioxane occurs above its performance standard in both the NBBW area and in groundwater more than 2.5 miles downgradient. Based on the discovery of 1,4-dioxane during the investigations, the WSDs implemented the North End response actions as a contingency measure on site and north of the site boundary. Extraction wells and associated collection and conveyance piping were installed in five extraction areas (Areas 1 through 5) to transport impacted water to the off-site POTW. The extent of 1,4-dioxane north of the site, as detected in 2018, is shown on Figure 6-7.



## 8.0 Human and Ecological Risks

This section summarizes the potential risks to human and ecological receptors. Sections 8.1 and 8.2 summarize the conclusions of the Baseline Risk Assessment<sup>30</sup> (RA) completed in 1992/1993. Since the Baseline RA, the remedy components identified in the ROD were implemented to address unacceptable risks and prevent exposure of current and future receptors to site contaminants. An updated exposure pathway assessment was completed as part of this CSM to qualitatively evaluate current exposure of potential receptors after the remedy has been implemented and O&M is ongoing. The current risks to current and future receptors from the potentially complete exposure pathways are described in Section 8.3.

### 8.1 Summary of Baseline Human Health Risks

This section summarizes the potential human health risks identified in the Baseline RA. The Baseline RA was conducted for each environmental medium at the LLSS to evaluate the potential for adverse health and environmental effects caused by actual or potential releases of and exposure to site-related chemicals under current and hypothetical future conditions (EPA 1994). Volume 1 (OUs 1 and 6) of the Baseline RA was issued for public comment in February 1992 (EPA 1992a). EPA received significant public comments on Volume 1 and amended the document with a Response to Comments, dated August 20, 1992 (EPA 1992b). Volumes 2A and 2B (OUs 2 and 3 and OUs 4 and 5) of the Baseline RA were issued for public comment in December 1992 (EPA 1992d). The final volume, Volume 2C (sitewide issues, lead, and radionuclides), of the Baseline RA was issued for public comment in April 1993 (EPA 1993). On July 2, 1993, EPA issued a Response to Comments document for Volumes 2A, 2B, and 2C.

The Baseline RA for the LLSS was completed after the interim measures were constructed (including drum removal, soil cover, NBBW, and SWRA) but before the final remedy components were implemented for the site. The Baseline RA was used to inform the selection of the remedy in the 1994 ROD. Subsequently, the remedy components described in Section 5.0 were implemented at the site to address exposure pathways and the unacceptable risks that were identified in the Baseline RA. The remedy was implemented to contain the waste and mitigate risk of exposure to contaminants by potential receptors.

The Baseline RA for the LLSS was based on the following assumptions:

- No further remedial actions would be implemented to address hazardous substances at the site.
- Interim remedial measures would be discontinued. Existing structures, such as fences and the NBBW, would not be maintained and would eventually deteriorate. The SWRA would also not be maintained and would eventually deteriorate.
- Existing physical structures would not be maintained and would eventually deteriorate.
- Hypothetical future use of the site would not be restricted, and any type of land use could occur, including agricultural, industrial, recreational, or residential.

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<sup>30</sup> Typically, a baseline assessment evaluates the types of risks that could be present now or in the future if a site is not cleaned up. Under the baseline scenarios, it is hypothesized that the use of the site would not be restricted, and no action was taken nor would be taken to mitigate risk from human or ecological exposure to contaminants. A baseline RA uses these assumptions to assess the need for remedial action, to provide a basis for determining cleanup levels, and for comparing potential health effects of various remedial alternatives.

The evaluation of human health risks included identification of COCs, assessment of exposure pathways, assessment of toxicity, and characterization of risk. The Baseline RA indicates what risks would exist if no action was taken at the site, that is, the remedy components would not have been implemented, operated, or maintained and the contamination would not be monitored or measured.

Separate risk assessments for lead and radionuclides were conducted. Exposure to lead cannot be evaluated through the same methodology used in the Baseline RA for other chemicals because research has not identified a threshold below which no adverse health effects occur. Similarly, exposure to radionuclides was evaluated differently than other contaminants because of their unique properties. The assessment of risks resulting from exposure to lead and radionuclides are discussed in Subsections 8.1.5 and 8.1.6.

#### 8.1.1 Identification of Contaminants of Concern

COCs for each OU were selected from all available LLSS data. Table 8-1 presents the COCs selected in the Baseline RA for each medium and the minimum and maximum detected values for each. The list of COCs has been modified since the Baseline RA to include newly detected contaminants that have been identified at the site (for example, 1,4-dioxane) or to remove contaminants based on site-specific analysis. Therefore, the current list of COCs for the LLSS (Table 3-1) is not the same as the original list of COCs identified in the Baseline RA (Table 8-1).

#### 8.1.2 Assessment of Exposure Pathways

The next step of the Baseline RA included evaluation of exposure pathways<sup>31</sup>. All potentially complete exposure pathways were evaluated in the Baseline RA and incomplete exposure pathways were not considered.

The Baseline RA evaluated current and future potential uses of the site and the area surrounding the LLSS. At the time of the Baseline RA, on-site receptors included employees of WMC who are on site during the work week. Off-site receptors identified in the Baseline RA included farm residents near the LLSS, agricultural workers, and people who may use the surrounding area for recreation. The Baseline RA concluded that no on-site exposures occur. WMC workers are subject to Federal and State regulations prescribing worker protection requirements to control exposure and, therefore, potential exposure pathways are not complete.

The Baseline RA assumed current residents, workers, and recreational users in the area around Lowry Landfill may be exposed to contaminants present at the site by several potential pathways. The exposure pathways evaluated included:

- Ingestion of groundwater
- Inhalation of contaminants volatilized from groundwater and dermal absorption during household water use (for example, while showering, washing, or bathing)
- Incidental ingestion of and dermal absorption from surface soil, surface water, and sediments

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<sup>31</sup> Exposure is defined as the contact of an organism (receptor) with a chemical or physical agent (EPA 1989). A complete exposure pathway has five elements: (1) contaminant source; (2) mechanism for contaminant release; (3) environmental transport mechanism; (4) exposure point (receptor location); and (5) feasible route of exposure (inhalation, ingestion, dermal absorption). Exposure cannot occur unless the pathway is complete.



- Inhalation of volatilized contaminants and wind-eroded particulate matter emitted from the site.

The Baseline RA also identified hypothetical future uses of the site, assuming no actions were taken to contain or control the waste or to limit the future use of the site. Hypothetical future exposure settings included:

- Hypothetical future on-site and off-site residents (adults and children):
  - Ingestion of groundwater
  - Incidental ingestion of surface soil, subsurface soils brought to the surface from excavation, sediment, and surface water
  - Inhalation of volatiles from surface water and sediment
  - Inhalation of suspended soil and/or dry sediments as particulates
  - Inhalation of landfill gas emissions
  - Dermal contact with surface soil, subsurface soil, surface water, sediment, and landfill gas
  - Encountering concentrated levels of methane
- Hypothetical future on-site commercial/industrial workers:
  - Ingestion of groundwater
  - Incidental ingestion of surface soil and subsurface soil
  - Inhalation of suspended surface soil as particulates
  - Inhalation of landfill gas emissions
  - Dermal contact with surface soil, subsurface soil, and landfill gas
  - Encountering concentrated levels of methane
- Hypothetical future on-site and off-site recreational users:
  - Incidental ingestion of surface soil, surface water, and sediment
  - Inhalation of suspended soil and/or dry sediment as particulates
  - Inhalation of landfill gas emissions
  - Inhalation of volatiles from surface water and sediment
  - Dermal contact with surface soil, surface water, sediment, and landfill gas

The Baseline RA for the LLSS quantified exposure by estimating the highest exposure that could reasonably occur, the reasonable maximum exposure (RME)<sup>32</sup>, and for some media, the typical exposure-approximating conditions that are most likely to occur to provide a range of potential exposures. Exposure point concentrations and exposure parameter values were selected so the total exposure represents the upper 90th percentile estimate of possible exposures. A detailed discussion of the methods used to calculate the RME, and exposure point concentrations can be found in Section 7 of the ROD (EPA 1994). A basic assumption of the risk assessments is that no physical, chemical, or biological processes are acting to reduce the chemical concentration over time, and therefore, exposure point concentrations are constant for the duration of exposure.

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<sup>32</sup> The RME is designed to be a conservative estimate of exposure that is within the range of possible exposures but is higher than typical exposures.

### 8.1.3 Summary of Toxicity Assessment and Risk Characterization

Chemical contaminants are divided into two groups according to their effects on human health: chemicals that have carcinogenic effects and those that have noncarcinogenic/systemic effects. Exposure to some of the chemicals detected at the LLSS could potentially result in both types of effects. Carcinogenic effects result in or are suspected to result in the development of cancer. Noncarcinogenic or systemic effects include a variety of toxicological end points and may include effects on specific organs or systems, such as the kidney, liver, and lungs.

For carcinogens, risks are estimated as the incremental probability of an individual developing cancer over a lifetime as a result of exposure to the carcinogen. Risks are probabilities that are generally expressed in exponential form ( $1 \times 10^{-4}$ ). An excess lifetime cancer risk of  $1 \times 10^{-6}$  indicates one *additional* cancer case in a population of one million as a result of site-related exposure to a carcinogen under specific exposure conditions at the LLSS. Under the National Oil and Hazardous Substances Pollution Contingency Plan, an acceptable risk range is defined as one in one million (1 in 1,000,000 or  $1 \times 10^{-6}$ ) to one in ten thousand (1 in 10,000,  $1 \times 10^{-4}$ ). Risks greater than one in ten thousand ( $1 \times 10^{-4}$ ) generally require some form of action to mitigate those risks. Estimated cancer risks of  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$  are within the risk management range and, depending on the circumstances, do not require action.

The potential for noncarcinogenic effects is evaluated by comparing an exposure level over a specified time period (for example, a lifetime) with a reference dose derived for a similar exposure period. The ratio of exposure to toxicity is called a hazard quotient (HQ). An HQ greater than 1 indicates the potential for an adverse noncarcinogenic health effect from exposure to the chemical. A Hazard Index (HI) is generated by adding the HQs for all COCs that affect the same target organ or system (for example, the liver or respiratory system) within a medium or across all media to which a given population may reasonably be exposed. If the HI for each toxic end point exceeds 1, the potential for an adverse noncarcinogenic health effect from exposure to the medium is indicated.

Table 8-2 summarizes the total risk for the hypothetical future on-site residential setting for all pathways quantified. Cancer risks from all pathways quantified were added together to obtain a cumulative risk for the exposure setting. The cancer risks presented represent RME conditions, the full 30-year exposure duration (child and adult) and the highest exposure point concentrations estimated for each on-site media. Noncancer HIs were added together to obtain a cumulative risk for each receptor (adult or child) within a pathway. (Adult and child HIs are not additive.) Landfill solids and landfill gas were not included in this summary table because risk from exposure to these media were evaluated on a screening level basis only and were not quantified.

The potential for adverse effects from exposure to subsurface soil and landfill gas were estimated differently than the other environmental media. For subsurface soil and landfill gas, the Baseline RA used risk-specific values and reference concentrations as screening tools. A risk specific value is a concentration that will result in a  $1 \times 10^{-6}$  excess lifetime cancer risk for carcinogenic effects. A reference concentration is a concentration that will result in an HQ of 1 for noncarcinogenic effects. Both risk-specific values and reference concentrations are calculated with the same media-specific intake parameters developed for the LLSS. Risk-specific values and reference concentrations were then compared to the exposure point concentrations calculated for subsurface soil and landfill gas.



#### 8.1.4 Summary of Risks for Each Operable Unit

The following discussion of OU groups presents the risks associated primarily with the hypothetical on-site residential exposure scenario for each OU medium. In almost all cases, the hypothetical on-site residential exposure scenario resulted in the greatest or most significant estimates of risks.

**OUs 1 and 6: Shallow Groundwater, Subsurface Liquids, and Deep Groundwater.** The highest excess lifetime cancer risk from ingesting water from a well within the source area (for hypothetical future on-site resident adult using RME conditions) was  $1 \times 10^{-2}$ , which exceeds EPA's risk management range of  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$ . Three COCs (arsenic, benzo[a]anthracene, and vinyl chloride) were responsible for about 70 percent of the total risk estimate. With 6 years of exposure, the HI for noncarcinogenic effects through ingestion could be as high as 47 for an adult and 46 for a child. Five COCs exceeded their reference dose and contribute to the total HI. Table 8-3 presents the excess lifetime cancer risk and noncancer HQ for the COCs with the greatest contribution to risk in subsurface liquids.

**OU2: Landfill Solids.** Landfill solids were evaluated as subsurface soil from 1 to 10 feet bgs. The potential adverse effects of landfill solids were evaluated on a screening level basis only. Table 8-4 presents the comparison of subsurface soil concentrations to risk-specific values calculated at a  $1 \times 10^{-6}$  risk and to reference concentrations.

Concentrations of four chemicals exceeded their carcinogenic risk-specific values for the ingestion or inhalation pathway in a hypothetical future on-site residential setting. Concentrations of arsenic, beryllium, and Aroclor-1260 in subsurface soil exceeded their risk-specific values for the ingestion pathway. Concentrations of arsenic, beryllium, and chromium (hexavalent) in subsurface soil exceeded their risk-specific values for the inhalation pathway. At selected sample locations, exposure to these chemicals in subsurface soil would result in an excess lifetime cancer risk greater than  $1 \times 10^{-5}$  for each individual chemical. None of the COCs evaluated in this manner exceeded their noncarcinogenic reference concentration for ingestion or inhalation for hypothetical future on-site residents.

Concentrations of two chemicals (Aroclor-1260 and chromium) exceeded their carcinogenic risk-specific values for the ingestion or inhalation pathway in a hypothetical future on-site occupational (commercial/industrial worker) setting. The concentration of PCBs in one sample exceeded its risk-specific value for the ingestion pathway. The concentration of chromium in 37 samples exceeded its risk-specific value for the inhalation pathway. Concentrations of Aroclor-1260 and chromium were co-located at one sample location. None of the COCs evaluated in this manner exceeded their noncarcinogenic reference concentration for ingestion or inhalation in an occupational setting.

**OU3: Landfill Gas.** The potential adverse effects of landfill gas were evaluated on a screening level basis only, similar to the evaluation of landfill solids. For the hypothetical future on-site residential setting, exposure point concentrations of all carcinogenic VOCs from within the landfill mass exceeded their carcinogenic risk-specific values for the inhalation pathway. Concentrations of five VOCs with noncarcinogenic effects from within the landfill mass exceeded their noncarcinogenic reference concentrations for inhalation (the HQ for each chemical is greater than 1). Table 8-5 presents the comparison of exposure point concentrations of landfill gas within the landfill mass to risk-specific values and reference concentrations.

At the time of the Baseline RA (before construction of the landfill gas extraction system), methane was detected above the lower explosive limit within and outside of the landfill mass, but not off site. It

therefore presented an explosion hazard under a prescribed set of conditions (i.e., concentrations between 5 and 15 percent by volume, the presence of a spark source, and sufficient oxygen levels).

Modeled concentrations of 1,1-dichloroethene and vinyl chloride within a hypothetical future *off-site* residence with a cracked structural slab exceeded their carcinogenic risk-specific values for the inhalation pathway. Exposure to these chemicals through inhalation would result in an excess lifetime cancer risk greater than  $1 \times 10^{-6}$  for each individual chemical. Modeled concentrations of noncarcinogenic VOCs did not exceed their noncarcinogenic reference concentrations for inhalation. Table 8-6 presents the comparison of exposure point concentrations to risk-specific values and reference concentrations.

**OU4: Soil.** Potential risks from contaminants in soil were evaluated at four separate areas according to the chemical distribution found in each area resulting from past disposal practices. The four areas are:

- The sewage sludge application/leachate injection area (Group 1)
- The sewage sludge application area (Group 2)
- The leachate spraying area (Group 3)
- The tire pile area (Group 4)

The highest excess lifetime cancer risks for a hypothetical future on-site resident was from ingesting or inhaling surface soil from the sewage sludge application/ leachate injection area (Group 1). The estimated risks for an adult receptor ingesting surface soil from Group 1 soil resulted in an estimated risk of  $2 \times 10^{-5}$ ;  $2 \times 10^{-5}$  for Group 2 soil;  $1 \times 10^{-5}$  for Group 3 soil; and  $6 \times 10^{-6}$  for Group 4 soil. The estimated excess lifetime cancer risk from inhalation of dust arising from the soil in Group 1 was  $1 \times 10^{-5}$ . Estimated cancer risks for all remaining soil groups were less than those calculated for Group 1. Chromium (assumed to be in the carcinogenic hexavalent form) is the primary contributor to the risk estimate for inhalation of dust. Table 8-3 presents the excess lifetime cancer risk for the COCs, within soil from the sewage sludge application/leachate injection area (Group 1), that contributed to the greatest risk estimates for the hypothetical future on-site residential setting. Table 8-3 also presents the noncancer HQs using for COCs in Group 1 surface soil that have the greatest contribution to risk in the hypothetical future on-site adult residential setting.

**OU5: Surface Water and Sediments.** For the Baseline RA, surface water data were grouped according to geographic location and creek flow. The three groups include:

- Data from the unnamed creek, from the toe of the landfill to the area previously occupied by Pond 3 (Group 1)
- Samples collected from Section 31, from the area previously occupied by Pond 3 to the confluence of the unnamed creek and Murphy Creek (Group 2).
- Data from Sections 31 and 30, from the confluence of the unnamed creek and Murphy Creek to the southern portion of Section 30 (Group 3).

The installation of the SWRA prevents contaminants in shallow groundwater from contacting surface water within the unnamed creek streambed (Group 1). Surface water in the unnamed creek streambed currently consists of stormwater from the landfill cover and surrounding area. However, the Baseline RA assumed that the SWRA would not be maintained and would deteriorate to pre-construction conditions.



The Baseline RA assumed the on-site portion of unnamed creek (Group 1) would be used by a child for recreational purposes. If true, a child in the hypothetical future on-site residential setting could experience an excess lifetime cancer risk of  $8 \times 10^{-4}$  from ingestion of vinyl chloride (85 percent contribution) and 1,1-dichloroethene (14 percent contribution) in surface water. An excess lifetime cancer risk of  $9 \times 10^{-6}$  could result from ingestion of arsenic (77 percent contribution) in sediments from the same section of the creek. Table 8-3 presents the excess lifetime cancer risk for the COCs within the on-site section of the unnamed creek (Group 1) for surface water and sediment exposure that contributed the most risk from recreational use by a child in the hypothetical future on-site residential setting.

The HI for noncarcinogenic effects was 2 for the hypothetical future on-site resident (child) ingesting acetone and trans-1,2-dichloroethene (each contributed 30 percent of the total HI) in surface water and 0.4 for ingesting antimony and arsenic (75 percent contribution) in sediments from recreational use on the on-site section of the unnamed creek (Group 1). Table 8-3 presents the noncancer HQ for each COC quantified in surface water and sediments for exposure to a child in the hypothetical future on-site residential setting.

Exposure to off-site surface water (Group 2 and 3) in a recreational setting resulted in estimated risks less than  $1 \times 10^{-6}$ . Exposure to off-site sediments assumed that sediments had spread beyond the creek banks during periods of high flow. Therefore, sediment data were used in a residential setting. Childhood exposure to off-site sediments (Group 2) in a residential setting resulted in an estimated risk of  $7 \times 10^{-5}$  from ingestion of arsenic and dioxins and  $4 \times 10^{-6}$  from inhalation of chromium and arsenic. Ingestion of arsenic, manganese, and vanadium by a child in a hypothetical residential setting resulted in a pathway HI for noncancer effects of 1. However, these chemicals affect different target organs.

Childhood exposure to off-site sediments (Group 3) in a hypothetical residential setting resulted in an estimated risk of  $2 \times 10^{-5}$  from ingestion of arsenic and beryllium and  $6 \times 10^{-6}$  from inhalation of chromium and arsenic. Ingestion of antimony, arsenic, and chromium by a child in a residential setting results in an HI for noncancer effects of 2. Antimony had an HQ of 1, while the remaining chemicals each had HQ significantly below 1. However, antimony was detected only once and uncertainty of the resulting HI from the contribution of antimony is high.

#### 8.1.5 Summary of Baseline Lead Risks

Exposure to lead cannot be evaluated through the same methodology used in the Baseline RA. Toxicity values cannot be determined because research has not identified a threshold below which no adverse health effects occur. Lead is also thought to be carcinogenic through prolonged low dose exposure; however, its noncarcinogenic effects on infants and children are more serious because they are manifested in a shorter time period than the onset of cancer.

Toxic effects of lead exposure are correlated with blood lead levels, and therefore, blood lead levels have been determined to be an appropriate benchmark for exposure. Adverse health effects in infants and children exposed (current and potential future) to lead in environmental media at the LLSS were estimated by the percent of children that would have a blood lead level greater than the "level of concern" of 10 micrograms per deciliter ( $\mu\text{g}/\text{dl}$ ) established by the EPA and Centers for Disease Control and Prevention (CDC).

Lead was detected in groundwater, soil, surface water, and sediments at the LLSS. The summary statistics for lead in each medium are presented on Table 8-1. The most conservative setting involving children to 7 years in age was the hypothetical future on-site residential setting. For the hypothetical future on-site residential setting, 6 percent of the children from birth to 7 years old were estimated to have blood lead levels above 10 µg/dl. Uptake of lead from groundwater had the greatest contribution to total lead uptake.

#### 8.1.6 Summary of Baseline Radiological Risks

A radiological risk assessment was prepared separately from the assessment of chemical risk from the LLSS. Radionuclides were detected in all media except landfill gas. The following steps were used to select the radionuclides in each media to be carried through the risk assessment: an evaluation of the detection frequency; a comparison to background concentrations; a determination of parent radionuclides; and an elimination of radionuclides with short half-lives. Table 8-8 lists the radionuclides detected in each medium.

Potential receptors and exposure pathways, and therefore, possible exposure settings, were the same as those described in the Baseline RA for other chemical contaminants. Further, it was assumed that all future off-site settings would result in lower exposures than future on-site exposures. Consequently, future off-site exposures were not evaluated for radionuclide exposure.

EPA classifies all radionuclides as human carcinogens based on their property of emitting ionizing radiation and the extensive weight of evidence provided by epidemiological studies of radiogenic cancers in humans. EPA generally evaluates potential human health risks based on radiotoxicity, considering only the carcinogenic effects of radionuclides. One exception to this is uranium, which is a kidney toxin as well as a carcinogen. Given that kidney toxicity may occur prior to the onset of cancer from exposure to uranium concentrations in drinking water, EPA calculated the HQ for chronic oral exposure to uranium.

Table 8-8 presents a summary of radiological risk from all exposure pathways. Total radiological risk estimated for background and on-site concentrations was the same ( $2 \times 10^{-3}$ ). Radionuclides present in media on site did not appear to present an increased risk over background, using exposure conditions outlined in this assessment.

The HQ resulting from ingestion of uranium at the RME for a hypothetical future on-site resident was estimated to be 2.3 for a child and 1.0 for an adult. These HQ values indicate the potential for an adverse noncarcinogenic health effect. The HQs for children or adults ingesting uranium in upgradient (or off-site) wells was estimated to be below 1 (0.4 and 0.2, respectively).

#### 8.1.7 Health Effects Related to Site Contaminants of Concern

Potential human health effects that are related to site CoCs are summarized from the baseline risk assessment (EPA 1992a) below. A more detailed discussion on potential health effects is presented in the site risk assessment documents.

- Chlorinated Solvents: Human and ecological receptors can be exposed to chlorinated solvents through inhalation, dermal exposure, and ingestion. Exposure to chlorinated solvents can damage the central nervous system, reproductive system, liver, and kidneys. Most chlorinated solvents have been identified as carcinogens or probable carcinogens by EPA.

- **BTEX Compounds:** BTEX compounds can cause neurologic, immunologic, reproductive, and hematologic effects in receptors. In addition, benzene is carcinogenic. Inhalation is the major exposure route, but ingestion and dermal exposure are also significant.
- **Metals and Metalloids:** The health effects of metals and metalloids vary. The form of the metal (chemical species, compound, matrix, and particle size) influences the metal's bioaccessibility, bioavailability, fate and effects (EPA 2007). Certain metal compounds accumulate in human tissues and this bioaccumulation can be related to the metal's toxicity. For example, mercury is a heavy metal that is highly toxic if inhaled or ingested. The organic form of mercury, methylmercury, bioaccumulates in ecosystems and can cause adverse effects on children exposed before birth or adults at higher concentrations. Similarly, lead is a naturally occurring element but may also be released to the environment from industrial sources, such as former lead smelters. Lead is particularly dangerous to children and can cause damage to their brains and nervous systems. Chromium can exist in the environment as trivalent chromium (chromium III), which is an essential nutrient that helps the body use sugar, protein, and fat, or as hexavalent chromium (chromium VI), which is toxic and causes cancer, liver and kidney damage. Hexavalent chromium is more soluble than trivalent chromium and leaches from the soil into the groundwater or surface water.
- **Pesticides:** The health effects of pesticides depend on the type of pesticide. Some, such as the organophosphates and carbamates, affect the nervous system. Others may irritate the skin or eyes. Some pesticides may be carcinogens. Others may affect the hormone or endocrine system in the body. Many pesticides can bioaccumulate within human or ecological receptors. Receptors may be exposed to pesticides through ingestion of food or soil or inhalation of dust particles containing pesticides.
- **PCBs:** PCBs have been demonstrated to cause a variety of adverse health effects. They have been shown to cause cancer in animals as well as a number of serious non-cancer health effects in animals, including effects on the immune system, reproductive system, nervous system, endocrine system and other health effects. Studies in humans support evidence for potential carcinogenic and non-carcinogenic effects of PCBs. The different health effects of PCBs may be interrelated. Alterations in one system may have significant implications for the other systems of the body.
- **Radionuclides:** Exposure to low-levels of radiation does not cause immediate health effects, but can cause a small increase in the risk of cancer over a lifetime. Studies show that radiation exposure increases the chance of getting cancer, and the risk increases as the dose increases: the higher the dose, the greater the risk. Understanding the type of radiation received, the way a person is exposed (external vs. internal), and for how long a person is exposed are all important in estimating health effects. A human can be exposed to radionuclides by inhaling dust in air, or ingesting water and food. Children and fetuses are especially sensitive to radiation exposure. The cells in children and fetuses divide rapidly, providing more opportunity for radiation to disrupt the process and cause cell damage.
  - The risk from exposure to a particular radionuclide depends on:
  - The energy of the radiation it emits.
  - The type of radiation (alpha, beta, gamma, x-rays).
  - Its activity (how often it emits radiation).



- Whether exposure is external or internal. External exposure is when the radioactive source is outside of your body. X-rays and gamma rays can pass through your body, depositing energy as they go. Internal exposure is when radioactive material gets inside the body by eating, drinking, breathing or injection (from certain medical procedures). Radionuclides may pose a serious health threat if significant quantities are inhaled or ingested.
- The rate at which the body metabolizes and eliminates the radionuclide following ingestion or inhalation.
- Where the radionuclide concentrates in the body and how long it stays there.
- 1,4-dioxane: EPA has classified 1,4-dioxane as a potential human carcinogen. Other health effects include damage to the liver, kidneys, mucus membranes of the nasal passages, and central nervous system (EPA 2013b).

Phenols and Phthalates: Several PAHs and some specific mixtures of PAHs are considered to be cancer-causing chemicals. PAHs may cause other health issues. For example, workers who have been exposed to large amounts of naphthalene from skin contact and inhalation have developed blood and liver abnormalities. Exposure to phenols can cause irritation to the skin, eyes, nose, throat, and nervous system. Severe exposure can cause skin burns and liver, kidney, and nervous system damage. Exposure to phthalates can result in damage to the reproductive system and impact child development (EPA 2012b).

## 8.2 Summary of Baseline Environmental Risks

The LLSS ecological assessment, included in Volume 2B of the Baseline RA (EPA 1992d), focused on potential effects on terrestrial wildlife from ingestion of contaminated media. This section summarizes the findings of the ecological assessment conducted as part of the Baseline RA.

### 8.2.1 Ecological Setting

Habitats within and surrounding the LLSS have been disturbed by past and ongoing landfill disposal activities. Habitats in the area surrounding the LLSS and the active DADS disposal sites are primarily native prairie with an intermittent riparian corridor, stripped prairie, fallow fields, weeded, disturbed prairie, and wetlands along Murphy Creek. No natural permanent surface water source exists within the LLSS boundary and there are no aquatic habitats within the LLSS boundaries that have the capacity to support fish. During the construction of the SWRA, a total of 0.87 acre of wetlands was disturbed. As part of the sitewide remedy, an equal area of wetlands was created along Murphy Creek, northeast of the site boundaries.

### 8.2.2 Ecological Contaminants of Concern

The ecological assessment was based on data collected during the RIs for OUs 2 and 3 and OUs 4 and 5. Because of the transient nature of terrestrial receptors, it was assumed that potential receptors would have access to the entire site. Only data from surface soil (0 to 1 foot), surface water, and sediment were used in the assessment. Ecological receptors would not be exposed to groundwater contaminants because of the depth to groundwater. Landfill gas was not addressed because of a lack of literature information on the toxicity of gas to ecological receptors. Landfill solids were not addressed because it was assumed that the most significant exposures for terrestrial organisms would result from the upper 1 foot of the soil column.

Chemicals detected in surface soil, surface water, and sediments were initially screened based on comparisons with background concentrations, frequency of detection, and relative toxicity for use in the ecological assessment. The relative toxicity of the chemicals was screened to eliminate inorganic constituents that are commonly found in the environment, act as macronutrients to living organisms, or are relatively nontoxic to environmental receptors. Table 8-9 lists the retained ecological contaminants of concern (ECOC) evaluated in each medium and their maximum detected concentration.

#### 8.2.3 Potential Ecological Receptors

The ecological assessment identified threatened and endangered species that may be present at or near the site; however, no specific occurrences of the listed candidate species were recorded within 1 mile of the LLSS at the time of the assessment. A list of threatened and endangered species identified in the Baseline RA that could be present in the vicinity of the LLSS is provided as Table 8-10. The area surrounding the LLSS could provide a habitat for these species, and therefore, they were considered potential ecological receptors.

Terrestrial wildlife were considered to be potential receptors because they can use the LLSS as habitat and thus be exposed to site-related contamination through daily activities. Other potential receptors include terrestrial and riparian vegetation growing in contaminated media. Aquatic organisms were not considered potential receptors to environmental contamination.

#### 8.2.4 Exposure Assessment

Exposure pathways for terrestrial wildlife may include:

- Foraging and ingestion of vegetation or invertebrates contaminated through biomagnification<sup>33</sup> or bioaccumulation
- Ingestion of vegetation, which may result in the incidental ingestion of surface soil and the inhalation of surface soil as dust or volatile constituents in surface soil
- Ingestion of surface water and inhalation of volatile constituents volatilizing from surface water
- Incidental ingestion of sediments while drinking or searching for food in the unnamed creek
- Dermal contact with soil, surface water, and sediment while burrowing or grooming

Terrestrial wildlife currently use and could continue to use the LLSS in the future, regardless of planned land use. Therefore, the ecological assessment focused on direct exposures (ingestion of media) to terrestrial wildlife. Because the habitat in the area occupied by the former landfill is highly disturbed and of relatively poor quality, exposures resulting from biomagnification and bioaccumulation of contaminants were considered minor and therefore, not addressed. Other exposure routes affecting terrestrial wildlife including inhalation and dermal contact and effects to vegetation were also not addressed because of the lack of quantitative literature values for quantifying exposure.

#### 8.2.5 Ecological Effects Assessment

The potential for adverse effects to terrestrial wildlife was assessed through comparison of potential intake through ingestion with an appropriate toxicity value. Toxicity values were obtained from the literature for all ECOCs in each media evaluated. The lowest observable adverse effect level (LOAEL), no observable adverse effect level, and the lethal dose that kills half of the population exposed (LD50) were

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<sup>33</sup> Biomagnification is the process by which a chemical concentration increases in plant or animals as it moves up the food chain.

obtained from toxicological investigations using laboratory or wild animal species. Toxicity data are media- and species-specific and were not available for all ECOCs.

Based on comparisons in this assessment, maximum detected concentrations of select inorganic and organic chemicals in surface soil, surface water, and sediments may result in adverse effects to terrestrial wildlife. For surface soil, the ingestion of aluminum, barium, cadmium, cobalt, iron, and octochlorodibenzodioxins exceeded their respective adjusted LOAEL value. The effects of acetone and ammonia in surface soil on environmental receptors could not be evaluated because of the lack of toxicological information for these two chemicals. For sediments, ingestion of aluminum, barium, cobalt, iron, lead, and heptachlorodibenzo-p-dioxin exceeded their respective adjusted LOAEL value. Due to the lack of toxicological information for acetone, ammonia, aniline, and benzene, these chemicals in sediments could not be evaluated for their effects on environmental receptors. For surface water, maximum concentrations of aluminum, antimony, barium, cobalt, iron, mercury, vanadium, benzene, 2-butanone, 1,2-dichloroethene (trans and total), 2,4-dichlorophenol, methylene chloride, 2-methylnaphthalene, 2-methyl phenol, 4-methylphenol, 4-methyl-2-pentanone, octochlorodibenzodioxins, phenol, tetrachloroethene, trichloroethene, toluene, and vinyl chloride exceeded calculated water criteria.

The baseline ecological assessment had a high level of uncertainty as a result of the many assumptions made when calculating the potential risks. These assumptions include the intake of contaminated media, the bioavailability of the chemicals, and the representativeness of the laboratory data for site conditions and receptors. These uncertainties may result in the over- or underestimation of ecological risk.

### 8.3 Updated Exposure Pathway Evaluation and Risk Assessment

This section describes how the risks posed through each pathway were eliminated, reduced, or controlled by the components of the sitewide remedy and in doing so protect human health and the environment. The potential risks from site contaminants and exposure pathways not mitigated by the remedy components are estimated and described in this section. The remedy was designed to achieve the remediation goals by eliminating the exposure pathway or reducing the risks to human health and the environment to achieve the performance standards. Achieving the performance standards results in cancer risk levels at or below  $1 \times 10^{-6}$  and noncancer hazards below 1 for individual contaminants at the LLSS, and cumulative risk for all exposures and contaminants to less than or between EPA's risk management range of  $1 \times 10^{-4}$  and  $1 \times 10^{-6}$  and an HI of less than 1.

The Baseline RA identified potentially complete exposure pathways and unacceptable risk to human health and the environment. The conclusions of the Baseline RA were used to identify RAOs (Table 3-3) and performance standards (Table 5-1). In general, the current COCs, migration pathways, exposure pathways, and potential receptors are similar to those identified in the Baseline RA and do not substantively change the evaluation of potential risks to human health and the environment. However, changes have been made to EPA's risk assessment methodology, toxicity values, and other factors that would affect the calculation of risk at the LLSS. Some of these factors were described in the 2001 Five-Year Review (EPA 2001b). In addition, changes have been made to the list of COCs based on site-specific analysis. These changes have been documented in previous decision documents (ROD Amendments or ESDs), the Five-Year Reviews, and the GWMP updates. The list of COCs on Table 3-2 reflect the current list of COCs as identified in the 2018 GWMP (EMSI and Parsons 2018).



The Baseline RA assumed future residential use of both the on-site and off-site areas. Current restrictions on land and groundwater use on-site and in certain off-site areas indicate that the exposure assumptions used at the time of the 1994 ROD are no longer valid and were very conservative (EPA 2007a). Land use is now restricted by ICs over the entire on-site area and in certain off-site areas (described in Section 5.6). Therefore, the exposure assumptions used at the time of the remedy selection do not represent the reasonably anticipated future land use under current conditions and are conservative (EPA 2007a).

The remedial actions and remedy components for the site mitigate potential risks to human health and the environment through:

1. Containment of contaminated groundwater and collection and treatment of that groundwater in an on-site treatment facility
2. Maintenance of the cover over the landfill mass
3. Containment and collection of landfill gases and treatment or destruction of those gases
4. Excavation, treatment, and off-site disposal of drums and associated contamination in the FTPA
5. Construction and operation of the WTP on site
6. Re-engineering of the drainage in unnamed creek to intercept and contain contaminated seepage and eliminate the release of contamination into sediments and surface water (the SWRA)
7. Implementation of a comprehensive monitoring program
8. Establishment of ICs to limit access, prohibit on-site construction, prohibit use of water beneath the site, and prohibit incompatible on-site and off-site land uses and activities.

Ongoing monitoring of groundwater, soil gas, soil, sediments, surface water, and the remedy components will provide an early warning of failure of the remedy. These requirements include, but are not limited to performance and compliance monitoring of the existing extraction systems and barrier walls, SWRA collection system, and existing groundwater treatment facility; soil and sediment erosion monitoring; surface water runoff monitoring; monitoring of gas migration; and groundwater monitoring for detection of potential vertical or horizontal contaminant migration.

The remedy components implemented to address potential exposure pathways or unacceptable risks for each OU are described below. The risks to human health or the environment are evaluated for potentially complete exposure pathways. Figures 8-1 through 8-3 show how the exposure pathways to current and hypothetical future on-site and off-site receptors are addressed by the remedy and ongoing maintenance and monitoring activities.

#### 8.3.1 OUs 1 and 6: Shallow Groundwater, Subsurface Liquids, and Deep Groundwater

This section describes the potential exposure pathways from groundwater and subsurface liquids to current and future on-site and off-site industrial/commercial workers, recreational users, and residents. Exposure of ecological receptors is not evaluated because the depth of the groundwater and subsurface liquids precludes contact with terrestrial animals and plants.

There are no complete exposure pathways from contaminated groundwater or subsurface liquids to on-site or off-site receptors, as shown on Figure 8-1. Potential exposure pathways to current and future receptors are addressed by the remedy components in place, groundwater use restrictions, and ongoing maintenance and monitoring.

The potential risks to hypothetical future residents in the North End Area were calculated to provide context for the concentrations of 1,4-dioxane and other VOCs detected in the groundwater north of the site. These calculations are described below. The assessment demonstrated that there is no significant exposure or risk from the concentrations of contaminants detected in the North End Area, even under highly conservative, unlikely, and hypothetical exposure scenarios.

#### *Evaluation of On-site Exposure Pathways*

The remedy components prevent the exposure of on-site receptors to contaminants in groundwater and subsurface liquids. Shallow groundwater beneath the LLSS is not currently used and ICs prevent its future use. ICs were placed on-site and off-site to prevent human exposure to groundwater. Restrictive covenants that run with the water rights prohibit drilling of new wells on site except as necessary to monitor or implement the selected remedy. These restrictive covenants apply to the Lower Dawson, Denver, Upper and Lower Arapahoe, and Laramie-Fox Hills aquifers beneath the site. Denver owns the water rights to these aquifers. The restrictive covenants include specific requirements for constructing and maintaining wells that penetrate more than one aquifer to prevent potential cross-contamination between aquifers. In addition, restrictive covenants that run with the water rights prohibit the installation of new groundwater wells in the Dawson and Denver aquifers (except as necessary to monitor or implement the selected remedy) within off-site properties owned by Denver, Waste Management Inc., or the Trust. Areas with land and groundwater use restrictions are shown on Figure 5-4.

The groundwater remedy components (NBBW, NTES, and extraction wells) extract groundwater for treatment and mitigate the off-site migration of contaminants. The upgradient perimeter slurry wall also inhibits off-site groundwater from flowing into the LLSS's subsurface environment. The WSDs conduct performance and compliance groundwater monitoring at the LLSS in accordance with the GWMP. To assess whether the RAOs for groundwater are being met, the data collected as part of the groundwater monitoring program are used to evaluate (1) compliance with performance standards along the POC; (2) the effectiveness of the four engineered components of the groundwater containment remedy (perimeter slurry wall, NTES, NBBW and MW38 extraction systems); (3) the protectiveness of the remedy; and (4) changes in water quality, if any, in deeper bedrock units beneath the site. There are 60 compliance wells in the network, which are monitored for 29 chemicals.

Containment and treatment of groundwater will continue to reduce the contaminant concentration in on-site groundwater. The greatest cancer risk estimated in the Baseline RA for groundwater exposure was  $1 \times 10^{-2}$  for hypothetical future long-term ingestion of on-site shallow groundwater originating from the waste pit source area. The baseline noncancer hazard index was estimated as 47 for this hypothetical future pathway. These risks are expected to decrease over time as existing groundwater within the shallow aquifer is treated and groundwater flow through the LLSS is reduced.

The selected remedy for OUs 1 and 6 specifies that appropriate measures shall be taken to prevent and remediate contaminant migration off site if contaminant levels exceed performance standards at compliance boundaries during implementation or operation of the groundwater remedy. Contingency measures that have been implemented at the LLSS include the perimeter slurry wall extraction wells, the MW38 sand channel extraction wells, the NBBW extraction wells, and the North End Response Actions. As described in Section 6.1, several wells contain contaminants at concentrations above the performance standards and were identified as out of compliance (EMSI and Parsons 2020). Out of

compliance conditions are evaluated and addressed by the agencies and the WSDs according to the GWMP.

#### *Evaluation of Off-site Exposure Pathways*

The evaluation of off-site exposure pathways focuses on the groundwater plume extending north from the site. Remedy features and the natural groundwater gradient inhibit off-site migration to the south, east, and west of the site. The groundwater north of the site boundary is monitored as part of the GWMP and was recently investigated as part of the North End investigation. The North End Area is shown on Figure 6-7. Groundwater north of the NBBW is extracted by wells within the North End Response Action areas (Areas 1 through 5; Figure 5-13). As described in Section 6.1, the only COC that exceeds groundwater performance standards is 1,4-dioxane. The extent of 1,4-dioxane in groundwater in the North End study area that exceeds the performance standard of 0.9 µg/L is shown on Figure 6-7. 1,4-dioxane has been detected only in the shallow groundwater; it has not been detected in the deep unweathered groundwater monitoring wells north of the LLSS (below approximately 50 feet bgs) (EMSI and CDM Smith 2020b).

There are no complete exposure pathways to off-site receptors from 1,4-dioxane in shallow groundwater north of Section 6. Personnel collecting groundwater samples and workers operating the North End Response Action extraction wells and water treatment facility use OSHA procedures and protective equipment to avoid exposure to 1,4-dioxane in groundwater. Recreational users (such as golfers or hikers) would not be exposed to groundwater during normal use of the area under current site conditions. Therefore, groundwater in the North End Area does not pose an unacceptable risk to commercial/industrial workers or recreational users.

There are no complete exposure pathways to off-site residents from 1,4-dioxane in groundwater, such as the domestic use of groundwater for drinking or bathing, or vapor intrusion<sup>34</sup> to indoor air. ICs associated with LLSS restrict the land and groundwater use within and surrounding the LLSS, including Section 31 north of the site. These restrictions do not extend over the northernmost portion of the 1,4-dioxane plume but other city or municipal codes restrict the use of groundwater north of the site, as shown on Figure 5-4. In particular, the City of Aurora's City Code Section 138-154(a) prohibits the development or use of any new (e.g., post-dating city ordinance 138-154) private water supply that will be used within the city limits without the written approval of the City's water director. However, City of Aurora's City Code Section 138-154(b) provides grandfather status to private water supply systems that pre-date city ordinance 138-154.

A well survey conducted in 2017 identified four private wells located within the footprint of the 1,4-dioxane plume and one well immediately adjacent to the plume (Figure 5-5). Two of the private wells have been sampled annually since 2006 and 1,4-dioxane has not been detected in these wells; the other three wells were abandoned (EMSI and TCHD 2020). The annual sampling of these private wells will continue as part of the maintenance and monitoring of the site. The two private wells were installed before the City of Aurora adopted City Code Section 138-154 and the residences associated with the private wells have not been annexed into the City of Aurora. If the residences are annexed into the City limits, provisions of the City's Annexation Agreement would require the Annexor to deed over the "non-

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<sup>34</sup> Volatile compounds in shallow groundwater may volatilize and enter indoor air through a process called vapor intrusion.



tributary and not non-tributary water within the Dawson-Arkose, Denver, Arapahoe, and Laramie-Fox Hills aquifers that lie beneath the Annexor's Property."

Residential areas north and east of the 1,4-dioxane plume (specifically, the Gun Club Estates) may contain private groundwater wells but the use of these wells is unknown. Based on the results of the North End Investigation, groundwater contamination from the LLSS is not affecting these residential areas. In 2020, EPA referred the Gun Club Estates area to the EPA and State of Colorado site assessment programs. The State of Colorado, in consultation with EPA, is in the initial stages of utilizing a wholly separate process to study the Gun Club Estates area and determine whether additional environmental investigation is warranted.

Vapor intrusion of 1,4-dioxane into indoor air is considered an incomplete exposure pathway based on the properties of 1,4-dioxane. In general, vapor intrusion of 1,4-dioxane is not considered a major route of exposure because of the relatively low potential of 1,4-dioxane to move from the groundwater phase to the vapor phase. Vapor intrusion and volatilization from groundwater or surface water are not considered significant sources of exposure to the general population because the Henry's Law constant of  $4.8 \times 10^{-6}$  atm·m<sup>3</sup>/mol at 25°C (approximately 77°F) and high water solubility of 1,4-dioxane (greater than 800 grams per liter) indicate that 1,4-dioxane will primarily remain in the aqueous phase and that volatilization to air will be limited (EPA 2018). EPA guidance recommends that the vapor intrusion pathway be considered for volatile chemicals with a Henry's Law Constant greater than  $10^{-5}$  atm m<sup>3</sup>/mol (EPA 2002c). Therefore, groundwater contaminated with 1,4-dioxane in direct contact with a building foundation or present in a dewatering sump would not result in significant exposure to residents. Based on these factors, the vapor intrusion pathway is considered incomplete.

#### *Evaluation of Hypothetical Risks to Off-site Receptors*

Although the exposure pathways are incomplete, the hypothetical risks to off-site residents were calculated to provide a conservative assessment of the potential risks from groundwater north of the site. The risk assessment calculations were based on an RME scenario, which used the 95<sup>th</sup> percentile upper confidence limit (UCL) on the mean exposure value to represent the exposure point concentration. Potential exposure pathways from groundwater to hypothetical future residents include direct contact (inhalation, ingestion, and dermal contact) with groundwater used as a drinking water source and vapor intrusion into indoor air.

The potential risks to hypothetical future residents using the groundwater as a drinking water source were calculated in this section even though domestic use is not a reasonably anticipated future use. The North End groundwater plume contains low levels of 1,4-dioxane. The highest concentration of 1,4-dioxane north of Yale Avenue in the 2018/2019 sampling effort was 7.4 µg/L at monitoring well MW129-WD in 2019. The average 1,4-dioxane concentration was calculated to be 1.4 µg/L and the 95<sup>th</sup> percentile UCL was 2.9 µg/L. The groundwater samples used in the risk evaluation were collected from the shallow, upper aquifer (weathered Denver formation), which is not used as a drinking water source in the vicinity of the North End groundwater plume. Groundwater samples from deeper wells did not contain detectable concentrations of 1,4 dioxane.

Using the Risk Assessment Information System (RAIS, [https://rais.ornl.gov/cgi-bin/prg/RISK\\_search](https://rais.ornl.gov/cgi-bin/prg/RISK_search)), the increased cancer risk was estimated for potential exposure pathways including ingestion, inhalation, and dermal exposure. If a future hypothetical resident used the shallow aquifer for drinking water at an assumed concentration of 2.9 µg/L, they might be exposed to an increased theoretical excess cancer risk

of  $6 \times 10^{-6}$  – meaning 6 people out of a total population of 1,000,000 exposed in this scenario might be expected to develop cancer related to 1,4 dioxane exposure from the shallow groundwater. The cancer risks for exposure through ingestion, inhalation, and dermal exposure are shown on Table 8-11. The noncancer hazard quotient was calculated to be 0.03.

The total cancer risk for hypothetical future residents is at the low end of the risk management range and the hazard quotient is below the acceptable limit of 1, indicating that action is not required. In addition, exposure to 1,4 dioxane in groundwater is not occurring and is not expected to occur in the future. The City of Aurora does not permit installation of groundwater wells in the shallow aquifer where 1,4-dioxane has been detected and 1,4-dioxane has not been detected in deeper groundwater monitoring wells in the North End Area.

The calculations of cancer risks and noncancer hazards were based on conservative assumptions, which are listed on Table 8-11. The risk assessment process uses standardized exposure factors to represent potential human exposure to contaminants. The exposure assessment includes assumptions for average body weight, ingestion rates of water and soil, inhalation rates, body surface areas, and frequency and duration of exposure, which are based on investigations of actual human exposure reported in scientific literature. As such, individuals vary their behavior and the assumptions used for exposure assessment may under- or over-estimate an individual's actual exposure. In addition, risks to potential receptors may be higher if the maximum detected concentration is used in the risk evaluation, rather than the 95th percentile UCL. For example, if a future, hypothetical resident utilized the shallow aquifer for drinking water and installed a well in the vicinity of MW129-WD, they may be exposed to 7.4 µg/L of 1,4-dioxane, which is the maximum concentration of 1,4-dioxane detected in the North End Area during the 2018/2019 sampling event. The estimated cancer risk to a hypothetical future resident would increase if the resident was exposed to the maximum concentration of 1,4-dioxane, rather than the 95th percentile UCL concentration. However, the probability that a future user would place a drinking water well in the area of maximum plume concentration is very low (as this well is on the northern boundary of DADS along Yale Avenue), which is why the risk assessment methodology uses the 95th percentile UCL on the mean contaminant concentration to estimate a high-end exposure.

Compounds other than 1,4-dioxane detected in groundwater may contribute to site risks. Groundwater in the North End Area contains low levels of 1,4-dioxane and six VOCs (all detected at levels below site performance standards): acetone, 1,1-DCA, naphthalene, PCE, toluene, and TCE. Acetone is a common laboratory contaminant and is not thought to be related to site contamination. Therefore, acetone was not included in the risk assessment calculations. Toluene is not a carcinogen so it would not contribute to the cancer risk but was evaluated for its noncancer hazards. The concentrations of the VOCs detected in North End Area groundwater are shown on Table 8-12.

The potential risks to hypothetical future residents represent the most conservative risk scenario. Therefore, potential risks to residents from the detected compounds were calculated using standard exposure assumptions. As described earlier, the assessment of risks from 1,4-dioxane in groundwater were calculated using the RME concentration (2.9 µg/L). However, due to the low frequency of detection for the other VOCs, the maximum detected concentration for each chemical (shown in bold font on Table 8-12) was used in the risk estimation. The maximum detected concentrations were screened with EPA Regional Screening Levels (RSL) for residential tap water use; naphthalene and 1,4-dioxane were the only contaminants that exceeded the RSLs. However, as a conservative measure, the

increased cancer risk for all detected compounds was estimated for potential exposure pathways including ingestion, inhalation, and dermal exposure and are shown in Table 8-13. The total cancer risk was calculated to be  $1 \times 10^{-5}$  and the noncancer hazard index from all contaminants for future residential exposure was calculated to be 0.3. The addition of other detected compounds increases the incremental cancer risks, but the total cancer risk is still within the risk management range and the noncancer hazard is less than 1, indicating that no action is necessary to address potential risks to hypothetical future residents from chemicals in groundwater. In addition, these calculations were based on conservative assumptions and the total risk to potential receptors from contamination originating from the LLSS is likely lower than shown on Table 8-13.

There is uncertainty in the source of volatiles detected in the shallow groundwater in the North End plume. As shown on Table 8-12, the compounds 1,1-DCA and TCE were only detected in monitoring well MW129-WD. In addition, the maximum concentration of PCE was detected in this well. Well MW129-WD is located at the Yale Avenue boundary, more than a mile south of the nearest residence. 1,1-DCA, PCE, and TCE were not detected in wells MW141-WD or MW141 UDEN, which are downgradient of MW129-WD (Figure 6-7). Therefore, it is unlikely that the compounds detected in groundwater at MW129-WD are indicative of contamination in the downgradient plume, near the residential developments. Furthermore, toluene and naphthalene were only detected in the deep monitoring wells north of East Mississippi Avenue (MW176-UDEN, MW177-UDEN, and MW178-UDEN). There were no detections of these chemicals in wells located between Yale Avenue and East Mississippi Avenue, indicating that the constituents identified in the northern-most wells likely do not originate from the LLSS. Hence, the risk associated with these constituents detected north of East Mississippi Avenue may not be attributed to the LLSS. Therefore, the inclusion of detected compounds other than 1,4-dioxane in the risk evaluation may over-estimate the actual site risks.

The potential risks of vapor intrusion to indoor air were calculated for 1,4-dioxane in shallow groundwater. Other VOCs were detected in the North End Area monitoring wells, as listed in Table 8-12. However, these compounds were only detected in monitoring wells more than a mile away from current residences (MW129-WD) or were only detected in deep groundwater monitoring wells (MW176-UDEN, MW177-UDEN, and MW178-UDEN) and were not detected in the paired shallow groundwater monitoring wells (MW176-DEN, MW177-DEN, and MW178-DEN). Therefore, the calculation of potential risks from vapor intrusion of contamination in shallow groundwater to indoor air is focused on 1,4-dioxane.

The EPA Vapor Intrusion Screening Level for 1,4-dioxane in deep groundwater is 2,900  $\mu\text{g/L}$  and the Michigan Vapor Intrusion Screening Level for shallow groundwater is 1,900  $\mu\text{g/L}$  (MDEQ 2016). Currently, the State of Colorado does not identify a Vapor Intrusion Screening Level for groundwater for 1,4-dioxane. The highest concentration of 1,4-dioxane in the North End Area groundwater (7.4  $\mu\text{g/L}$ ) is significantly lower than these screening levels. Therefore, there is no evidence of unacceptable risk to receptors and ambient air, soil gas, or indoor air data have not been collected for the LLSS.

As a conservative evaluation of the potential risks to hypothetical future residents, the concentration of 1,4-dioxane in groundwater that would result in unacceptable risk from vapor intrusion to indoor air was calculated. Unacceptable risk was defined as either cancer risks higher than  $1 \times 10^{-4}$  or 1 in 10,000 or a noncancer hazard quotient above 1. These calculations assumed that shallow groundwater containing 1,4 dioxane was in direct contact with the foundation of a residence but there is no evidence to indicate



that this assumption is true. The calculations concluded that the concentration 1,4-dioxane in groundwater would need to be approximately 159,000 µg/L to result in an unacceptable hazard to residents through inhalation of indoor air (EPA 2019a). The concentrations of 1,4-dioxane in water that correspond to the acceptable noncancer hazard range of 0.1 to 1.0 is 15,900 to 159,000 µg/L. In contrast, the highest concentration of 1,4-dioxane detected in groundwater in the North End Area was 7.4 µg/L (in monitoring well MW129-WD in 2019). Therefore, vapor intrusion of 1,4-dioxane into indoor air would not pose an unacceptable risk to residents.

The calculated risks to hypothetical future off-site residents were within or below the acceptable risk management range. Furthermore, concentrations of 1,4-dioxane and other VOCs are expected to decrease over time. Groundwater north of the site boundary (within Section 31) will continue to be extracted by the North End Response Action extraction systems. The North End response actions were implemented as a contingency measure in response to exceedances of the performance standards at the compliance boundary. Systems in the five extraction areas (Areas 1 through 5) were installed to reduce off-site migration of 1,4-dioxane, reduce the mass of 1,4-dioxane north of the site, and to bring into compliance any monitoring well showing exceedances of the performance standard. Charts of 1,4-dioxane concentrations in the first half 2020 SSR indicate declining concentrations of 1,4-dioxane in the North End monitoring wells (EMSI and Parsons 2020). The potential for ongoing migration and potential actions to address 1,4-dioxane north of Section 31 were investigated during the North End Investigation (EMSI and CDM Smith 2020b). During this investigation the 1,4-dioxane plume north of LLSS was defined as a shallow groundwater plume that is limited vertically to the weathered bedrock and shallow un-weathered bedrock which terminates south of East Mississippi Avenue (EMSI and CDM Smith 2020b).

### 8.3.2 OUs 2 and 3: Landfill Solids and Landfill Gas

There are no complete exposure pathways for current or future receptors from landfill solids or landfill gas at the LLSS because the exposure pathways have been addressed by the remedy, as shown on Figure 8-2. The remedy components for OUs 2 and 3 included soil covers over landfill solids, excavation of surface and subsurface drums and contaminated soils within the FTPA waste pits, off-site treatment and disposal of excavated materials, and reclamation of the FTPA. In August 2005, EPA issued an Amendment to the ROD that changed the remedy for the north and south waste pits to on-site treatment and disposal of the solids excavated from the waste pits. The remedy also included installation of a landfill gas collection system and monitoring wells within the former landfill. Landfill gas is extracted from a network of 64 vertical extraction wells, all located within the refuse area. The extracted landfill gas is treated by a combination of two candlestick flares and a landfill GTEP.

Excavation of contaminated solids from the FTPA eliminated the potential for future direct contact, incidental ingestion, and inhalation. The baseline carcinogenic risk estimated for a hypothetical future on-site resident (the most conservative scenario) within the FTPA was  $2 \times 10^{-5}$  for ingestion and inhalation (inorganics and organic chemicals). These risks were eliminated with excavation of the contaminated solids. In addition, excavation of contaminated solids eliminated the solids as a potential source of further groundwater contamination.

The cover over the landfill mass eliminated the possible exposure of human or ecological receptors to physical and chemical hazards associated with contaminated solids and landfill waste. Ongoing maintenance and monitoring ensures the protectiveness of the cover. The landfill cover is monitored for the presence of burrowing animals that may contact the contaminated material. In addition, the

cover reduces infiltration of precipitation and thus reduces the potential for leachate generation and migration.

The landfill gas collection and treatment systems minimize landfill gas migration into the off-site subsurface environment, thus reducing the mobility and volume of toxic substances through their treatment. The remedy also removes contaminants from the gas through operation of the flares and landfill GTEP. The remedy eliminates the risk of fire or explosion from the accumulation of methane by reducing methane concentrations to less than 5 percent of the lower explosive limit at the boundary of the landfill mass. These reductions also minimize the potential threat of inhalation of contaminants in landfill gas by future receptors.

According to the Baseline RA, the estimated concentration of each carcinogenic contaminant in landfill gas within a hypothetical future on-site residence would exceed a  $1 \times 10^{-6}$  cancer risk level for each carcinogenic contaminant. This also would be true for a hypothetical future off-site home (200 feet west) if the structural slab of the home was cracked, and gas diffused inside the structure. Installation of the gas collection and treatment systems reduce the off-site risk of cancer from these pathways. Collection of landfill gas also reduces the potential for gas to contaminate groundwater.

Restrictive covenants that run with the land restrict on-site land use to landfilling, monitoring or remediation activities, or other uses not inconsistent with the remedy selected in the ROD. These restrictive covenants prevent human exposure to landfill solids and landfill gas within LLSS. The ICs prohibit the use of the site for day care centers, schools, nursing homes, hospitals, or residential purposes. The restrictive covenants also prohibit the construction of any structure and any excavation except as necessary for landfilling or to implement the selected remedy. EPA and CDPHE have the authority to enforce these on-site land use restrictions.

As an additional measure of protection to enhance the effectiveness of the selected remedy for landfill solids and landfill gas, restrictive covenants have been placed on off-site areas owned by Denver or the Trust. The restrictive covenants run with the land and restrict land use to landfilling, monitoring or remediation activities, industrial, commercial, utilities, agricultural, open space, or recreation uses. Transportation uses are allowed on Trust-owned property. These areas include a one-mile area to the north, a ½-mile area to the west and south, and a ¼-mile area to the east of the LLSS (Figure 5-4).

### 8.3.3 OUs 4 and 5: Soil, Surface Water, and Sediments

This section describes the potential exposure pathways from contaminants in soil, surface water, and sediment to current and future on-site and off-site human and ecological receptors. There are no complete exposure pathways to current and future *on-site* receptors from contaminated soil, surface water, or sediment; these pathways are addressed by the remedy components in place and ongoing maintenance and monitoring. In addition, there are no complete exposure pathways to current and future off-site receptors from contaminants in soil or sediment because the remedy prevents the migration of contaminants in soil and sediment off site. However, current and future off-site receptors may be exposed to contamination in surface water. The exposure pathways to potential receptors are shown on Figure 8-3.

This section includes calculations to quantify the potential risks to off-site workers, recreational users, and ecological receptors from contamination in surface water. The potential risks to off-site residents from contaminants in surface water were not calculated because the use of surface water as a drinking

water source is not a reasonably anticipated exposure scenario. Residents who live near the off-site surface water would only be exposed to the contamination as a recreational user (that is, while golfing or wading in the creek). The risk assessment concluded that the total cancer risks are less than the acceptable risk management range and the noncancer hazards are less than 1, indicating no unacceptable risks to off-site receptors from surface water. Potential risks to ecological receptors from 1,4-dioxane in surface water are not significant.

#### *Evaluation of On-site Exposure Pathways*

The potential risks to human health and the environment from soil, surface water, and sediments at the LLSS are mitigated by the remedy in place and the ongoing maintenance and monitoring activities. The remedy components for OUs 4 and 5 include:

- Continued maintenance of the existing cover on the landfill mass;
- Continued maintenance of other cover areas, including the unnamed creek drainage, vegetated areas, and the FTPA, including visual monitoring for soil and sediment erosion;
- Periodic monitoring of surface water runoff;
- Continued operation and maintenance of the SWRA and the NBBW; and
- Mitigation of 0.87 acres of wetlands loss through construction of 0.87 acres of new wetlands (which relocates wetland habitat away from the LLSS contamination).

As described in Section 8.3.2, the cover over the landfill mass eliminated the possible exposure of human or ecological receptors to soil at the LLSS and ongoing maintenance and monitoring ensures the protectiveness of the cover. The cover of the landfill mass is inspected, maintained, and repaired as necessary to promote stormwater runoff, prevent soil erosion, and limit the number of burrowing animals at the site. The cover also reduces infiltration of precipitation, leachate generation, and migration of contaminants from soil to groundwater.

The SWRA eliminates the potential future threat of exposure from direct contact and incidental ingestion of contaminated surface water and sediments at the LLSS. The baseline cancer risks associated with the hypothetical future ingestion of on-site surface water and sediments (as they existed before the SWRA) were estimated to be  $8 \times 10^{-4}$  and  $9 \times 10^{-6}$ , respectively. The baseline noncancer hazard index for ingestion of surface water was estimated to be 2 in the Baseline RA, and the baseline noncancer hazard index for the ingestion of sediments was estimated to be less than 1. Baseline cancer and noncancer risks have been reduced to acceptable levels by the SWRA (EPA 1994). The hydraulic connection between groundwater and surface water within the unnamed creek has been eliminated. Sediments within unnamed creek have been covered as a result of the SWRA, and thus, potential exposure to sediments in Section 6 has been eliminated. These measures will continue to be operated and maintained, as required by the ROD. ICs and access restrictions were implemented to eliminate potential human exposure to surface water and contaminated sediments in Section 31. Ongoing monitoring will provide a mechanism to detect contaminant migration.

#### *Evaluation of Off-site Exposure Pathways*

Current and potential future exposure to surface water within Murphy Creek is possible for groundskeepers or adults who golf at the Murphy Creek Golf Course that extends along Murphy Creek from Section 30 into Section 19 and for adults and children who reside in the nearby development or use the area for recreation. For the golf course groundskeeper and recreational golfers, the potentially



complete exposure pathways are dermal contact and incidental ingestion of surface water while performing maintenance or retrieving golf balls from the water. Likewise, for children and adult recreational users, the potentially complete exposure pathways are dermal contact and incidental ingestion while wading or playing within Murphy Creek. In addition, ecological receptors (aquatic and terrestrial) may be exposed to contamination in surface water. Murphy Creek is not currently used as a drinking water supply and it is not reasonably anticipated that it will be used as such in the future. In 2006, 2015 and 2016, surface water north of the LLSS were sampled for COCs. The surface water sampling locations and results are shown on Figure 6-9 and included surface water from Murphy Creek and ponds within or servicing the Murphy Creek golf course. Only 1,4-dioxane was detected above the groundwater performance standards. In 2016, only one surface water sample, SWMC-04, contained concentrations of 1,4-dioxane above the groundwater performance standard at 3.1 µg/L.

Concentrations of 1,4-dioxane at surface water sampling location SWMC-04 have decreased since 2006, from a high of 6.2 µg/L on March 30, 2006, to 3.1 µg/L on May 9, 2016. The 1,4-dioxane concentration in surface water at this location is similar to the concentrations detected in nearby groundwater monitoring well MW142-WD in 2016 (3.3 µg/L). Therefore, it is assumed that as the groundwater concentrations decrease through operation of the North End Response Action extraction systems, the concentrations detected in surface water (and sediment) would also decrease. Potential impacts to surface water will continue to be controlled through groundwater extraction and assessed through ongoing groundwater monitoring.

Sediment samples have not been collected in the North End Area; however, the low concentrations of 1,4-dioxane detected in the surface water, its miscibility in water, and its low potential for adsorption to organic carbon indicate the sediment concentrations would also be low. The European Chemicals Bureau (ECB) (2002) has estimated toxicity threshold estimates for 1,4-dioxane in sediment and soil based on equilibrium partitioning, with a predicted no effect concentration of 43 mg/kg in sediment and 14 mg/kg in soil. Generally low observed environmental concentrations of 1,4-dioxane, combined with low absorption potential in soil and sediment, suggest that these media are not relevant for ecological risk. Because 1,4-dioxane does not bioaccumulate, the potential for long-term effects on birds and mammals is low and of limited further ecological or wildlife concern (ECB 2002).

#### *Evaluation of Hypothetical Risks to Off-site Receptors*

The potential risks to off-site receptors from exposure to 1,4-dioxane in surface water were calculated. The risk assessment focused on the golf course groundskeeper, adult recreational user (golfer), and adolescent recreational user as the most likely and most conservative exposure scenarios. The potential risks to ecological receptors also were evaluated.

The surface water in Murphy Creek and ponds near and adjacent to the golf course contain low levels of 1,4-dioxane. The concentrations of 1,4-dioxane detected in surface water are presented on Figure 6-9. The maximum concentration of 1,4-dioxane detected in surface water was 10 µg/L at sampling location SWMC-03 in 2006; however, the highest concentration detected in recent samples was 3.1 µg/L at sampling location SWMC-04 in 2016. Using the recent surface water data collected in 2016, the average concentration of 1,4 dioxane in surface water from Murphy Creek was calculated to be 0.7 µg/L and the 95<sup>th</sup> percentile UCL on the mean surface water concentration was 1.9 µg/L. In the most recent sampling event, 1,4-dioxane was either not detected in the golf course ponds or was detected at a concentration just above the method detection limit (JPond-02/SWMC-08, 0.17 µg/L J [estimated] on May 4, 2016).

Therefore, the human exposure point values used for this risk evaluation were based on the surface water concentrations from Murphy Creek. Although risk calculations were conducted to evaluate the potential risks from exposure to 1,4 dioxane in surface water, there is no indication that significant human exposure to this water is occurring.

Of the potential workers in the North End Area, the golf course groundskeeper has the highest potential for exposure to surface water bodies and irrigation water from the on-site reclaimed water pond. Using the RAIS, the calculated 95<sup>th</sup> percentile UCL concentration (1.9 µg/L), and the conservative exposure assumptions listed on Table 8-14, the potential risks were estimated for incidental ingestion of and dermal contact with surface water. The total cancer risk for the golf course groundskeeper was  $4 \times 10^{-7}$ , which is below the acceptable risk management range, and the noncancer hazard quotient was calculated to be 0.0003, which is well below the acceptable noncancer risk of 1, indicating that no action is necessary to address potential risks to groundskeepers from 1,4-dioxane in surface water. The risks for each exposure pathway are listed in Table 8-14.

A recreational visitor (e.g., a golfer) may be exposed to surface water containing 1.9 µg/L of 1,4 dioxane through incidental ingestion or dermal contact while playing golf. Based on the conservative assumptions listed on Table 8-15, the golfer's increased cancer risk was  $5 \times 10^{-9}$ , which is below the acceptable risk management range. The noncancer hazard quotient was calculated to be 0.0005, which is below the acceptable value of 1. The potential risks to the adult recreational user are summarized on Table 8-15.

If an adolescent recreational user were exposed to 1.9 µg/L of 1,4 dioxane in the surface water bodies near the golf course, the estimated cancer risk is estimated to be slightly higher than for the adult golfer described above. The estimated cancer risks and exposure assumptions for an adolescent recreational user through incidental ingestion and dermal contact are shown on Table 8-16. The total increased cancer risk was calculated to be  $1 \times 10^{-8}$  and the noncancer hazard quotient was calculated to be 0.00002. The total hypothetical cancer risk and noncancer hazard are below the acceptable risk management levels.

The aquatic toxicity of 1,4-dioxane has been estimated at 201 milligrams per liter (mg/L) for algae to 666 mg/L for fish based on the EPA's Ecological Structure Activity Relationships estimation program (EPA 2019b). In the United States, only Michigan has a chronic water quality value for mammals, which is set at 22 mg/L (2,200 µg/L) (Michigan Department of Environment, Great Lakes, and Energy 2019). In contrast, the highest concentration of 1,4-dioxane detected in surface water in the North End Area was 10 µg/L (that is, 0.01 mg/L) at SWMC-03 in 2006. Therefore, ecological risk is not expected from surface water exposures in the North End Area.

There is uncertainty in the calculation of risks from surface water because 1) there is a limited data set and 2) there are a number of factors that influence surface water concentrations that include sources of contamination not related to the LLSS. The concentrations of 1,4-dioxane in Murphy Creek may vary over time, creating some uncertainty in the assessment of potential risks to receptors exposed to surface water. The 1,4-dioxane concentrations detected in 2006 were higher than those detected at the same locations in 2016. For example, at SWMC-03, 1,4-dioxane was detected at concentrations of 10 µg/L and 9.4 µg/L in 2006 but the concentration decreased to 0.49 µg/L (J-qualified or estimated) in 2016. Similarly, at SWMC-04, 1,4-dioxane was detected at 6.2 and 5.3 µg/L in 2006 and at 3.1 µg/L in 2016. In addition, if the maximum detected concentration of 1,4-dioxane in surface water (10 µg/L) was

used to estimate risk for the groundskeeper, golfer, and adolescent recreational user, the cancer risks would increase to  $2 \times 10^{-6}$ ,  $3 \times 10^{-8}$ , and  $5 \times 10^{-8}$ , respectively. However, these risks are still at the low end or below the acceptable risk range.

The calculated risks from 1,4-dioxane in surface water to off-site workers, recreational users, and ecological receptors were below acceptable levels. Furthermore, if the shallow groundwater is the source of the surface water in Murphy Creek, the concentrations should decrease as the groundwater concentrations decrease in the shallow groundwater plume over time as groundwater response actions continue at the LLSS and in the North End Response Action areas.

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**Table 8-1. Minimum/Maximum Concentrations of Contaminants of Concern**

Chemical	OU's 1/6	OU's 2/3		OU's 4/5		
	Subsurface Liquids (µg/L)	Subsurface Soil (µg/kg)	Landfill Gas (µg/m <sup>2</sup> )	Surface Soil (µg/kg)	Surface Water (µg/L)	Sediment (µg/kg)
<b>Organics</b>						
1,1-Dichloroethane	2/1,100,000		300/770,000		1/150,000	
1,1-Dichloroethene	0.8/14,000		170/18,000		6.4/5,000	2/1,800
1,2-Dichloroethane	3/1,800,000	42/30	110/68,000			
1,2-Dichloroethene	1/160,000				2/730	
1,4-Dichlorobenzene						
1,1,1-Trichloroethane		3.9/3.9	38/270,000		4/31,000	6,110,000
1,1,2-Trichloroethane	3/100					
1,2,4-Trichlorobenzene	8.5/1,700					
1,1,2,2-Tetrachloroethane	66/66					
2,4-Dichlorophenol	22/160				26/190	170/2,700
2,4-Dimethylphenol					14/920	
2,4-Dinitrophenol	500/500					
2,3,7,8-TCDD	$5 \times 10^6 / 1.1 \times 10^{-3}$			0.02/14	0.04/0.04	0.1/5.6
2-Butanone (MEK)	17/230,000	44/120	1/38,000	1/1	3.1/51,000	33/15,000
2-Chlorophenol	8/8					
2-Hexanone	49/270				4/7,400	
2-Methylnaphthalene	3/44,000				4.7/10	54/24,000
2-Methylphenol					87/4,100	
4,4'-DDD		0.26/1.2				
4,4'-DDE		0.11/0.11				
4,4'-DDT		0.34/30				
4-Chloroatiline		53/2,500				
4-Methylphenol					380/6,600	
4-Methyl-2-pentanone	4/960,000	2.7/170			3.7/27,000	
Acetone	4/3,000,000	15/160			3/240,000	
Aldrin		0.15/3.7				
Aniline						330/330
Benzene	1/970,000	1/1	10/190,000		1.5/180	2/6,100
Benzo(a)anthracene	84/84					
Benzo(b)fluoranthene		52/52				
Benzoic acid		81/210				
Benzyl alcohol	7.2/1,900					
beta-BHC		1.1/6				
bis(2-chloroethyl)ether	3/3					
bis(2-Ethylhexyl)phthalate	1/22,000			46/2,200		49/95,000
Butylbenzylphthalate		48/170				
Carbazole	7/12					
Carbon disulfide			22/160,000	9/25		

**Table 8-1. Minimum/Maximum Concentrations of Contaminants of Concern (continued)**

Chemical	OUs 1/6	OUs 2/3		OUs 4/5		
	Subsurface Liquids (µg/L)	Subsurface Soil (µg/kg)	Landfill Gas (µg/m <sup>2</sup> )	Surface Soil (µg/kg)	Surface Water (µg/L)	Sediment (µg/kg)
Carbon tetrachloride	15/26,000					
Chloroethane	2/260					
Chloroform	0.6/56,000	214	19/4,000	1/3		
di-n-Butylphthalate		45/110				
di-n-Octylphthalate	5.7/1,200	43/43				
Dibenzofuran	$2.0 \times 10^{-6}$ / $1.4 \times 10^{-3}$					
Dieldrin		9.5/9.5				
Endrin		0.11/0.15				
Endrin ketone		0.21/0.21				
Ethylbenzene					1.1/340	4/95,000
Ethylene dibromide	0.12/0.28					
Fluoranthene	26/200	69/69				69/7,700
gamma Chlordane		0.13/0.13				
gamma-BHC		0.11/0.11				
Methylene chloride	3/440,000	1.2/120	42/840,000		1/7,700	
Naphthalene	2.0/110,000					
PCB-1260		270/2,100		200/7,600		170/2,400
Pentachlorophenol	4/4,100					
Phenanthrene	4.2/1,700	46/46				62/6,200
Phenol		40/95			73/4,100	
Pyrene		75/75				
Tetrachloroethylene	0.9/340,000	1.9/1.9			0.7/2,300	3/48,000
Toluene	0.9/11,000,000	1/4	19/1,400,000	2/11	1/28,000	3/280,000
Trans-1,2-Dichloroethene					5.7/56,000	
trans-1,3-Dichloropropane	2.2/3.0					
Trichloroethylene	4/7,700,000				0.6/2,500	
Vinyl chloride	2.6/1,800		77/680,000		27/9,600	2/57
Xylenes			17/120,000		1.3/9,700	4/580,000
<b>Inorganics (Metals)</b>						
Aluminum		6,400/ $2.5 \times 10^7$		7,900/ $2.8 \times 10^7$	32/260,000	$3.2 \times 10^7$
Antimony		30/30,000			26/82	29/32,000
Arsenic	2.2/1,600	0.86/18,000		1.4/14,000	4/42	2/21,000
Barium		43/1,200,00		120/1,200,00	54/1,500	79/860,00
Beryllium		0.78/2,100		0.72/13,000		0.79/2,700
Cadmium		0.82/3,900		0.98/13,000		1.5/3,900
Chromium (IV)						
Chromium (total)	0.71/1,700	6.6/83,000		8.8/130,000	3/200	2.5/42,000

**Table 8-1. Minimum/Maximum Concentrations of Contaminants of Concern (continued)**

Chemical	OUs 1/6	OUs 2/3		OUs 4/5		
	Subsurface Liquids (µg/L)	Subsurface Soil (µg/kg)	Landfill Gas (µg/m <sup>2</sup> )	Surface Soil (µg/kg)	Surface Water (µg/L)	Sediment (µg/kg)
Cobalt	5.4/330	5.81/17,000		5/120,000	6.7/210	4/18,000
Copper		13/97,000		13/150,000	2.5/660	
Cyanide		0.52/2,400		0.9/4,900	8/250	0.29/2,300
Fluoride					0.66/660	
Lead	1/510	8.3/100,000		7.3/150,000	5/290	6.7/2,950,0
Manganese	180/70,000	120/1,800,000		200/2,700,000	6.9/38,000	380/1,900,000
Mercury		0.1/1,100		0.13/1,000		0.1/1,900
Nickel	13/2,000	7.7/29,000		7.1/130,000		2.8/42,000
Silver		2.3/16,000		3.1/9,800		
Thallium	0.34/760					
Vanadium		20/85,000		19/140,000	1.2/630	12/71,000
Zinc		43/180,000		44/340,000		13/540,000
<b>Radionuclides</b>						
Radionuclides	NA	NA		NA	NA	NA
<b>Notes:</b> This table was modified from Table 7-6 of the ROD (EPA 1994).						



**Table 8-2. Cumulative Total Risk for the Hypothetical Future On-site Residential Setting**

Exposure Media/Exposure Pathway	Reasonable Maximum Exposure	
	Excess Lifetime Cancer Risk	Noncancer HI
Ground Water Ingestion	$1 \times 10^{-2}$	47
Surface Soil Ingestion	$2 \times 10^{-5}$	0.1
Inhalation	$1 \times 10^{-5}$	0.06
Surface Water Ingestion	$8 \times 10^{-4}$	2
Sediments Ingestion	$9 \times 10^{-6}$	0.4
Cumulative Total	<b><math>2 \times 10^{-2}</math></b>	<b>49</b>
<p>Note:</p> <p>This table was modified from Table 7-14 of the ROD (EPA 1994).</p>		

**Table 8-3. Summary of Qualified Site Risks Based on Hypothetical Future On-site Residential Setting**

Exposure Pathways <sup>a</sup>	Chemicals of Concern	Reasonable Maximum Exposure	
		Excess Lifetime Cancer Risk	Noncancer Hazard Quotient
Organics			
Ingestion of subsurface liquids as a drinking water source <sup>b</sup>	Benzo(a)anthracene	2 x 10 <sup>-3</sup>	NA
	Arsenic	2 X 10 <sup>-3</sup>	10
	Vinyl chloride	2 x 10 <sup>-3</sup>	NA
	2,3,7,8-TCDD <sup>c</sup>	1 x 10 <sup>-3</sup>	NA
	1,2-Dichloroethane	6 x 10 <sup>-4</sup>	NA
	1,1-Dichloroethene	6 x 10 <sup>-4</sup>	0.25
	bis(2-chloroethyl)ether	3 x 10 <sup>-4</sup>	NA
	Pentachlorophenol	2 x 10 <sup>-4</sup>	0.12
	Tetrachloroethene	1 x 10 <sup>-4</sup>	0.52
	Thallium	NC	24
	2,4-Dinitrophenol	NC	3.0
	Carbon tetrachloride	6 x 10 <sup>-5</sup>	1.5
	Manganese	NC	1.2
Pathway Total <sup>d</sup>		1 x 10 <sup>-2</sup>	47
Surface Soil Ingestion <sup>e</sup>	Arsenic	8 x 10 <sup>-6</sup>	0.04
	Beryllium	5 x 10 <sup>-6</sup>	<0.01
	2,3,7,8-TCDD	4 x 10 <sup>-6</sup>	NA
	PCB-1260	2 x 10 <sup>-6</sup>	NA
	Chromium	NC	0.02
Pathway Total <sup>d</sup>		2 x 10 <sup>-5</sup>	0.1
Particulate Inhalation <sup>f</sup>	Chromium <sup>g</sup>	1 x 10 <sup>-5</sup>	NA
	Manganese	NC	0.04
	Barium	NC	0.02
Pathway Total <sup>d</sup>		1 x 10 <sup>-5</sup>	0.06
Surface Water Ingestion as a Child	Vinyl chloride	7 x 10 <sup>-4</sup>	NA
	1,1-Dichloroethene	1 x 10 <sup>-4</sup>	0.12
	2,3,7,8-TCDD <sup>e</sup>	2 x 10 <sup>-5</sup>	NA
	trans-1,2-Dichloroethene	NC	0.61
	Acetone	NC	0.52
	4-Methyl-2-pentanone	NC	0.12
	1,1,1-trichloroethane	NC	0.075
	Manganese	NC	0.05
Pathway Total <sup>d</sup>		8 x 10 <sup>-4</sup>	2

**Table 8-3. Summary of Qualified Site Risks Based on Hypothetical Future On-site Residential Setting (continued)**

Exposure Pathways <sup>a</sup>	Chemicals of Concern	Reasonable Maximum Exposure	
		Excess Lifetime Cancer Risk	Noncancer Hazard Quotient
Inorganics (Metals)			
Sediment Ingestion as a Child	Arsenic	7 x 10 <sup>-6</sup>	0.15
	Antimony	NC	0.16
	Chromium	NC	0.03
	Manganese	NC	0.03
Pathway Total <sup>d</sup>		9 x 10 <sup>-6</sup>	0.4
Maximum Cumulative Total		2 x 10 <sup>-2</sup>	49

**Notes:**

This table was modified from Table 7-10 of the ROD (EPA 1994).

<sup>a</sup> Exposure pathways presented are for adults using reasonable maximum exposures (RMEs).

<sup>b</sup> Subsurface liquids consist of shallow groundwater, waste-pit liquids and deep groundwater from source area wells.

<sup>c</sup> Dioxin equivalents.

<sup>d</sup> Not all COCs that contribute to the total risk are listed, therefore, sum of risk (or HQs) for listed chemicals will not equal the total.

<sup>e</sup> Using Group 1 exposure point concentrations.

<sup>f</sup> Dust arising from Group 1 surface soil.

<sup>g</sup> As hexavalent chromium.

NC = Not carcinogenic through this pathway.

NA = Not applicable.



**Table 8-4. Comparison of Subsurface Soil Maximum Detected Concentrations to Carcinogenic Risk-Specific Values and Noncarcinogenic Reference Concentrations in the Hypothetical Future On-site Residential Setting**

Chemical	Reasonable Maximum Exposure <sup>a</sup>				
	Maximum Detected Concentration	Risk-Specific Value <sup>b</sup> (µg/kg)	Exceeds Risk-Specific Value?	Reference Concentration <sup>b</sup> (µg/kg)	Exceeds Reference Concentration?
1,1,1-Trichloroethane	3.9	NA	—	7,029,702	No
1,2-Dichloroethane	130	6,986	No	NA	—
2-Butanone	6,700	NA	—	31,923,383,879	No
4,4'-DDD	1.2	2,654	No	NA	—
4,4'-DDE	0.11	1,873	No	NA	—
4,4'-DDT	30	1,870	No	39,063	No
4-Chloroaniline	2,500	NA	—	312,500	No
4-Methyl-2-pentanone	540	NA	—	3,900,284	No
Acetone	15,000	NA	—	7,821,500	No
Aldrin	3.7	37	No	2,344	No
Aluminum	24,700,000	NA	—	NA	—
Antimony	30,000	NA	—	31,250	No
Arsenic	18,000	358	Yes	23,438	No
Barium	1,190,000	NA	—	4,073,201	No
Benzene	1	21,922	No	NA	—
Benzo(b)fluoranthene	52	87	No	NA	—
Benzoic acid	210	NA	—	312,500,000	No
Beryllium	2,100	148	Yes	390,625	No
Beta-BHC	6	353	No	NA	—
Butylbenzylphthalate	170	NA	—	15,625,000	No
Cadmium	3,900	53,990	No	39,063	No
Chloroform	4	101,899	No	781,250	No
Chromium (Total)	83,000	8,098	Yes	390,625	No
Cobalt	17,000	NA	—	NA	—
Copper	97,000	NA	—	NA	—
Cyanide	2,400	NA	—	1,562,500	No
Di-n-butylphthalate	110	NA	—	7,812,500	No
Di-n-octylphthalate	62	NA	—	NA	No
Dieldrin	9.5	40	No	3,906	No
Endrin	0.15	NA	—	23,438	No
Endrin Ketone	0.21	NA	—	NA	—
Fluoranthene	69	NA	—	3,125,000	No
Gamma chlordane	0.13	NA	—	NA	—
Gamma-BHC (Lindane)	0.11	490	No	23,438	No
Lead	101,000	NA	—	NA	—
Manganese	1,770,000	NA	—	4,847,016	No

**Table 8-4. Comparison of Subsurface Soil Maximum Detected Concentrations to Carcinogenic Risk-Specific Values and Noncarcinogenic Reference Concentrations in the Hypothetical Future On-site Residential Setting (continued)**

Chemical	Reasonable Maximum Exposure <sup>a</sup>				
	Maximum Detected Concentration	Risk-Specific Value <sup>b</sup> (µg/kg)	Exceeds Risk-Specific Value?	Reference Concentration <sup>b</sup> (µg/kg)	Exceeds Reference Concentration?
Mercury	1,100	NA	—	23,380	No
Methylene chloride	120	84,891	No	4,687,500	No
Nickel	29,000	NA	—	1,562,500	No
PCB-1260 (Aroclor 1260)	2,100	83	Yes	NA	—
Phenanthrene	46	NA	—	NA	—
Phenol	95	NA	—	46,875,000	No
Pyrene	75	NA	—	2,343,750	No
Silver	16,000	NA	—	390,625	No
Tetrachloroethene	1.9	12,488	No	781,250	No
Toluene	4	NA	—	15,605,904	No
Vanadium	85,000	NA	—	546,875	No
Zinc	179,000	NA	—	15,625,000	No
bis(2-Ethylhexyl) phthalate	1,800	45,496	No	1,562,500	No

**Notes:**

This table was modified from Table 7-11 of the ROD (EPA 1994).

<sup>a</sup> Reasonable maximum exposure parameters and maximum detected concentrations.

<sup>b</sup> Risk-specific values and reference concentrations assume ingestion of soil and inhalation or airborne contaminants absorbed to dust.

NA = No toxicity values with which to calculate a value.

-- = Not applicable.

**Table 8-5. Comparison of Exposure Point Concentrations of Landfill Gas Within the Landfill Mass to Carcinogenic Risk-Specific Values and Noncarcinogenic Reference Concentrations in the Future On-site Residential Setting**

Reasonable Maximum Exposure <sup>a</sup>					
Chemical	95 UCL Gas Concentration (µg/m <sup>3</sup> )	Risk-Specific Value (µg/m <sup>3</sup> )	Exceeds Risk-Specific Value?	Reference Concentration (µg/m <sup>3</sup> )	Exceeds Reference Concentration?
1,1,1-Trichloroethane	3.7 x 10 <sup>4</sup>	NA	—	1,043	Yes
1,1-Dichloroethane	1.3 x 10 <sup>5</sup> (M)	NA	—	521	Yes
1,1-Dichloroethene	8.7 x 10 <sup>3</sup>	0.05	Yes	NA	—
1,2-Dichloroethane	1.5 x 10 <sup>3</sup> (M)	0.09	Yes	NA	—
2-Butanone	3.8 x 10 <sup>4</sup> (M)	NA	—	1,043	Yes
Benzene	1.3 x 10 <sup>4</sup>	0.29	Yes	NA	—
Carbon disulfide	2.2 x 10 <sup>4</sup>	NA	—	NA	—
Chloroform	1.2 x 10 <sup>3</sup> (M)	0.11	Yes	NA	—
Ethylbenzene	4.1 x 10 <sup>3</sup>	NA	—	1,043	Yes
Methylene chloride	4.4 x 10 <sup>5</sup> (M)	5.18	Yes	NA	—
Toluene	9.0 x 10 <sup>4</sup>	NA	—	417	Yes
Xylenes	5.0 x 10 <sup>3</sup>	NA	—	NA	—
Vinyl chloride	4.4 x 10 <sup>5</sup>	0.03	Yes	NA	—
<p>Notes:</p> <p>This table was modified from Table 7-12 of the ROD (EPA 1994).</p> <p><sup>a</sup> RME uses reasonable maximum exposure parameters and 95 UCL concentrations.</p> <p>(M) = Maximum concentrations used; 95 UCL exceeds maximum concentration.</p> <p>NA = No inhalation toxicity value with which to calculate a value.</p>					



**Table 8-6. Comparison of Modeled Exposure Point Concentrations Assuming a Cracked Slab to Carcinogenic Risk-Specific Values and Noncarcinogenic Reference Concentrations in the Future Off-site Residential Setting**

Chemical	Reasonable Maximum Exposure <sup>a</sup>				
	Modeled Gas Concentration (µg/m <sup>3</sup> )	Risk-Specific Value (µg/m <sup>3</sup> )	Exceeds Risk-Specific Value?	Reference Concentration (µg/m <sup>3</sup> )	Exceeds Reference Concentration?
1,1,1-Trichloroethane	3.6	NA	--	1,043	No
1,1-Dichloroethene	1.2	0.05	Yes	NA	--
Vinyl chloride	31.0	0.03	Yes	NA	--
<p>Notes:</p> <p>This table was modified from Table 7-13 of the ROD (EPA 1994).</p> <p><sup>a</sup> RME uses reasonable maximum exposure parameters and 95 UCL modeled gas concentrations.</p> <p>NA = No inhalation toxicity values with which to calculate a value</p> <p>-- = Not Applicable</p>					

**Table 8-7. Risk Assessment Radionuclides**

Radionuclide	OUs 1/6	OUs 2/3		OUs 4/5		
	Subsurface Liquids	Subsurface Soil	Landfill Gas	Surface Soil	Surface Water	Sediment
Americium-241	X					
Cadmium-109					X	
Cesium-137				X	X	
Europium-159						X
Lead-210	X	X				
Plutonium-239	X	X			X	
Potassium-40	X	X			X	X
Radium-226	X			X		X
Strontium-90	X	X			X	
Thorium-228	X	X				X
Thorium-230	X	X				
Thorium-232	X	X			X	X
Tritium	X				X	
Uranium-234	X	X		X	X	X
Uranium-235	X			X	X	X
Uranium-238	X	X		X	X	X
<p>Note:</p> <p>This table was modified from Table 7-16 of the ROD (EPA 1994).</p>						

**Table 8-8. Summary of Radiological Risk at the RME Hypothetical Future On-site Residential Setting**

Exposure Media	Exposure Pathway	Excess Cancer Risk	
		On-site	Background
Groundwater	Ingestion	$5 \times 10^{-4}$	$2 \times 10^{-4}$
Surface Soil	Ingestion	$4 \times 10^{-7}$	$5 \times 10^{-7}$
	Inhalation	$7 \times 10^{-7}$	$6 \times 10^{-7}$
	External	$4 \times 10^{-4}$	$5 \times 10^{-4}$
Surface Water	Ingestion	$2 \times 10^{-7}$	NA
Sediments	Ingestion	$9 \times 10^{-7}$	$8 \times 10^{-7}$
	Inhalation	$2 \times 10^{-6}$	$1 \times 10^{-6}$
	External	$1 \times 10^{-3}$	$9 \times 10^{-4}$
<b>Total Exposure</b>		$2 \times 10^{-3}$	$2 \times 10^{-3}$
<p>Note:</p> <p>This table was modified from Table 7-21 of the ROD (EPA 1994).</p>			



**Table 8-9. Maximum Detected Concentrations of Ecological Chemicals of Concern**

Chemical	Surface Soil (mg/mg soil)	Surface Water (µg/L)	Sediment (mg/mg sediment)
<b>Organics</b>			
1,1-Dichloroethane		15,000	0.0000034
1,1-Dichloroethene		5,000	
1,2-Dichloroethene (total)		730	0.00000057
1,1,1-Trichloroethane		31,000	0.00011
2,4-Dichlorophenol		400	0.0000027
2,4-Dimethylphenol		920	0.0000038
2-Butanone	0.0000000065	51,000	0.000015
2-Hexanone		10,000	
2-Methylnaphthalene		400	0.000024
2-Methylphenol			0.0000038
4-Chloroaniline	0.0000025		
4-Methylphenol		66,000	
4-Methyl-2-pentanone		27,000	
Acetone	0.00000014	240,000	0.0000084
Aniline			0.00000033
Benzene		5,000	0.00000061
Benzoic acid		6,300	
bis(2-ethylhexyl)phthalate	0.0000022		0.000095
Carbon disulfide	0.000000025		
Chloroform	0.0000000035		
di-n-Butylphthalate	0.0000020	4,000	0.0000027
Ethylbenzene		5,000	0.000095
Fluoranthene			0.0000077
Heptachlorodibenzofurans	0.00000000030		
Heptachlorodibenzo-p-dioxins	0.0000000029		0.0000000056
Hexachlorodibenzodioxins	0.00000000030		0.00000000070
Hexachlorodibenzofurans	0.00000000010		
Methylene chloride	0.00000015	77,000	
Naphthalene		400	0.000014
Octochlorodibenzodioxins	0.000000014	0.040	0.00000000060
Octochlorodibenzofurans	0.00000000020		
PCB-1260	0.0000076		0.0000024
Pentachlorodibenzodioxins	0.00000000010		
Phenanthrene			0.0000062
Phenol		4,100	
Pyrene			0.0000055
Toluene	0.000000011	28,000	0.00028
Tetrachloroethene		2,300	0.000048

**Table 8-9. Maximum Detected Concentrations of Ecological Chemicals of Concern (continued)**

Chemical	Surface Soil (mg/mg soil)	Surface Water (µg/L)	Sediment (mg/mg sediment)
trans-1,2-Dichloroethene		56,000	0.0000031
Trichloroethene		5,000	0.000041
Vinyl chloride		9,600	0.0000012
Xylenes		9,700	0.00058
<b>Inorganics (Metals)</b>			
Aluminum	0.027	260,000	0.032
Ammonia	0.0000032	25,000	0.000051
Antimony		150	0.000032
Arsenic	0.000014	42	0.000021
Barium	0.0016	1,500	0.00086
Beryllium		130,000	0.0000027
Boron	240		
Cadmium	0.000013		0.0000042
Chromium (total)	0.00013	210	0.00042
Cobalt	0.00012	210	0.000018
Copper	0.00015	660	0.00016
Cyanide	0.0000049	250	0.0000023
Iron	0.039	360,000	0.042
Lead	0.00015	290	0.0030
Magnesium		38,000	0.0019
Mercury	0.0000010	3.6	0.0000019
Nickel	0.00013	250	0.000042
Silver	0.0000098		
Tin	0.000014	250	0.000018
Vanadium	0.00014	620	0.000071
Zinc	0.35	1,300	0.00054
<p><b>Note:</b></p> <p>This table was modified from Table 7-24 of the ROD (EPA 1994). Blanks indicate chemical not of concern in the medium.</p>			

**Table 8-10. Potentially Occurring Threatened and Endangered Species Within or Around the Lowry Landfill Superfund Site**

Birds
Peregrine falcon ( <i>Falco peregrinus</i> )
Bald Eagle ( <i>Haliaeetus leucocephalus</i> )
Black tern <sup>a</sup> ( <i>Chlidonia niger</i> )
Mountain plover <sup>a</sup> ( <i>Charadrius montanus</i> )
White-faced ibis <sup>a</sup> ( <i>Plegadis chihi</i> )
Baird's sparrow <sup>a</sup> ( <i>Ammodramus bairdii</i> )
Whooping crane ( <i>Cms Americana</i> )
Long-billed curlew ( <i>Numenius americanus</i> )
Ferruginous hawk ( <i>Buteo regalis</i> )
Amphibians
Western boreal toad <sup>a</sup> ( <i>Bufo boreas boreas</i> )
Insects
Regal fritillary butterfly <sup>a</sup> ( <i>Speyeria Idalia</i> )
Mammals
Preble's meadow jumping mouse ( <i>Zapus hudsonius preblei</i> )
Swift fox <sup>a</sup> ( <i>Vulpes velos</i> )
Black-footed ferret ( <i>Mustela nigripes</i> )
Vegetation
Diluvium lady's tresses <sup>b</sup> ( <i>Spiranthes diluvialis</i> )
Colorado butterfly plant <sup>c</sup> ( <i>Gaura neomexicana ssp, Coloradensis</i> )

Note:

This table was modified from Table 7-22 of the ROD (EPA 1994). Species listed were identified as threatened or endangered at the time of the ROD.

<sup>a</sup> Species that are candidates for official listing as threatened or endangered species (Federal Register, Vol. 54, No. 4, January 6, 1989; Vol 55, No. 35, February 21, 1990).



<sup>b</sup> Listed by USFWS as Category 2, under review for protective status, Final Remedial Investigation Report for the Shallow Ground Water and Subsurface Liquids and Deep Groundwater Operable Units, Lowry Landfill, Vol. VI of VIII. Lowry Coalition, Boulder, CO).

<sup>c</sup> Listed by USFWS as Category 1, under review for protective status with sufficient information to support proposing to list the taxa as Threatened and Endangered.

Draft for Public Review

**Table 8-11. Risk Assessment Summary for Hypothetical Off-site Future Residents Using Shallow Aquifer**

Exposure Pathway	Excess Cancer Risk
Ingestion	$4 \times 10^{-6}$ (4 in 1,000,000)
Inhalation	$2 \times 10^{-6}$ (2 in 1,000,000)
Dermal Contact	$1 \times 10^{-8}$ (1 in 100,000,000)
<b>Total Excess Cancer Risk</b>	<b><math>6 \times 10^{-6}</math></b> <b>(6 in 1,000,000)</b>
<p>Notes:</p> <p>The noncancer hazard quotient was 0.03.</p> <p>The hypothetical future residents considered in the evaluation included a child (age 0 to 6 years, assumed to weigh 15 kilograms, consuming 0.78 liters per day, showering, and exposed to contaminated groundwater 350 to 365 days a year for 6 years) and an adult (age 6 to 26 years, weighing 80 kilograms, consuming 2.5 liters per day, showering, and exposed to contaminated groundwater 350 to 365 days a year for 20 years).</p> <p>The acceptable risk management range is <math>1 \times 10^{-6}</math> to <math>1 \times 10^{-4}</math> (cancer risks) or hazard index less than 1 (noncancer hazards).</p>	

**Table 8-12. Detected Concentrations of Volatile Organic Compounds in North End Area Groundwater**

Monitoring Well	Sample Date	Chemical	Concentration (micrograms per liter)
MW129-WD	9/12/2018	1,1-Dichloroethane	<b>1.7</b>
		Tetrachloroethene	<b>0.63 J (estimated)</b>
		Trichloroethene	<b>0.35 J (estimated)</b>
MW176-DEN	3/19/2018	Tetrachloroethene	0.31 J (estimated)
MW176-UDEN	5/2/2019	Toluene	<b>0.23 J (estimated)</b>
		Naphthalene	0.76 J (estimated)
MW177-UDEN	2/19/2019	Naphthalene	0.57 J (estimated)
MW178-UDEN	2/19/2019	Naphthalene	<b>0.77 J (estimated)</b>
Notes: <b>Bold text</b> indicates the maximum detected concentration of each chemical.			



**Table 8-13. Risk Assessment Summary for Hypothetical Off-site Future Residents Using Shallow Groundwater, Including Other Detected Volatile Organic Compounds**

Compound	Exposure Pathway			Total Hypothetical Excess Cancer Risk
	Ingestion	Inhalation	Dermal Contact	
1,1-Dichloroethane	$1 \times 10^{-7}$	$5 \times 10^{-7}$	$9 \times 10^{-9}$	$6 \times 10^{-7}$
1,4-Dioxane	$4 \times 10^{-6}$	$2 \times 10^{-6}$	$1 \times 10^{-8}$	$6 \times 10^{-6}$
Naphthalene	$1 \times 10^{-6}$	$5 \times 10^{-6}$	$7 \times 10^{-7}$	$7 \times 10^{-6}$
Tetrachloroethene	$2 \times 10^{-8}$	$3 \times 10^{-8}$	$1 \times 10^{-8}$	$6 \times 10^{-8}$
Toluene*	---	---	---	---
Trichloroethene	$5 \times 10^{-7}$	$4 \times 10^{-7}$	$5 \times 10^{-8}$	$7 \times 10^{-7}$
<b>Total Excess Cancer Risk</b>	<b><math>5 \times 10^{-6}</math> (5 in 1,000,000)</b>	<b><math>8 \times 10^{-6}</math> (8 in 1,000,000)</b>	<b><math>8 \times 10^{-7}</math> (8 in 10,000,000)</b>	<b><math>1 \times 10^{-5}</math> (1 in 100,000)</b>

**Notes:**

The noncancer hazard index (from all compounds) was 0.3.

\* Toluene is not a carcinogen, so the cancer risks were not calculated. The hazard quotient for toluene was 0.0001.

The hypothetical future residents considered in the evaluation included a child (age 0 to 6 years, assumed to weigh 15 kilograms, consuming 0.78 liters per day, showering, and exposed to contaminated groundwater 350 to 365 days a year for 6 years) and an adult (age 6 to 26 years, weighing 80 kilograms, consuming 2.5 liters per day, showering, and exposed to contaminated groundwater 350 to 365 days a year for 20 years).

The acceptable risk management range is  $1 \times 10^{-6}$  to  $1 \times 10^{-4}$  (cancer risks) or hazard index less than 1 (noncancer hazards).

**Table 8-14. Risk Assessment Summary for Golf Course Groundskeeper**

Exposure Pathway	Excess Cancer Risk
Ingestion	$4 \times 10^{-7}$ (4 in 10,000,000)
Dermal Contact	$1 \times 10^{-9}$ (1 in 1,000,000,000)
<b>Total Excess Cancer Risk</b>	<b><math>4 \times 10^{-7}</math></b> <b>(4 in 10,000,000)</b>
<p>Notes:</p> <p>The noncancer hazard quotient was 0.0003.</p> <p>The risk assessment assumes the groundskeeper is an adult with a body weight of 80 kilograms and is exposed to the surface water 252 days per year (6 days a week for 42 weeks) for 25 years. It is assumed the groundskeeper would be exposed to the contaminated surface water with a 1,4-dioxane concentration of 1.9 micrograms per liter for 6 hours per day and would ingest 0.11 liter of surface water per hour. The skin surface area exposed would include 813 square centimeters of the hands, forearms, feet, and lower legs.</p> <p>The acceptable risk management range is <math>1 \times 10^{-6}</math> to <math>1 \times 10^{-4}</math> (cancer risks) or hazard index less than 1 (noncancer hazards).</p>	

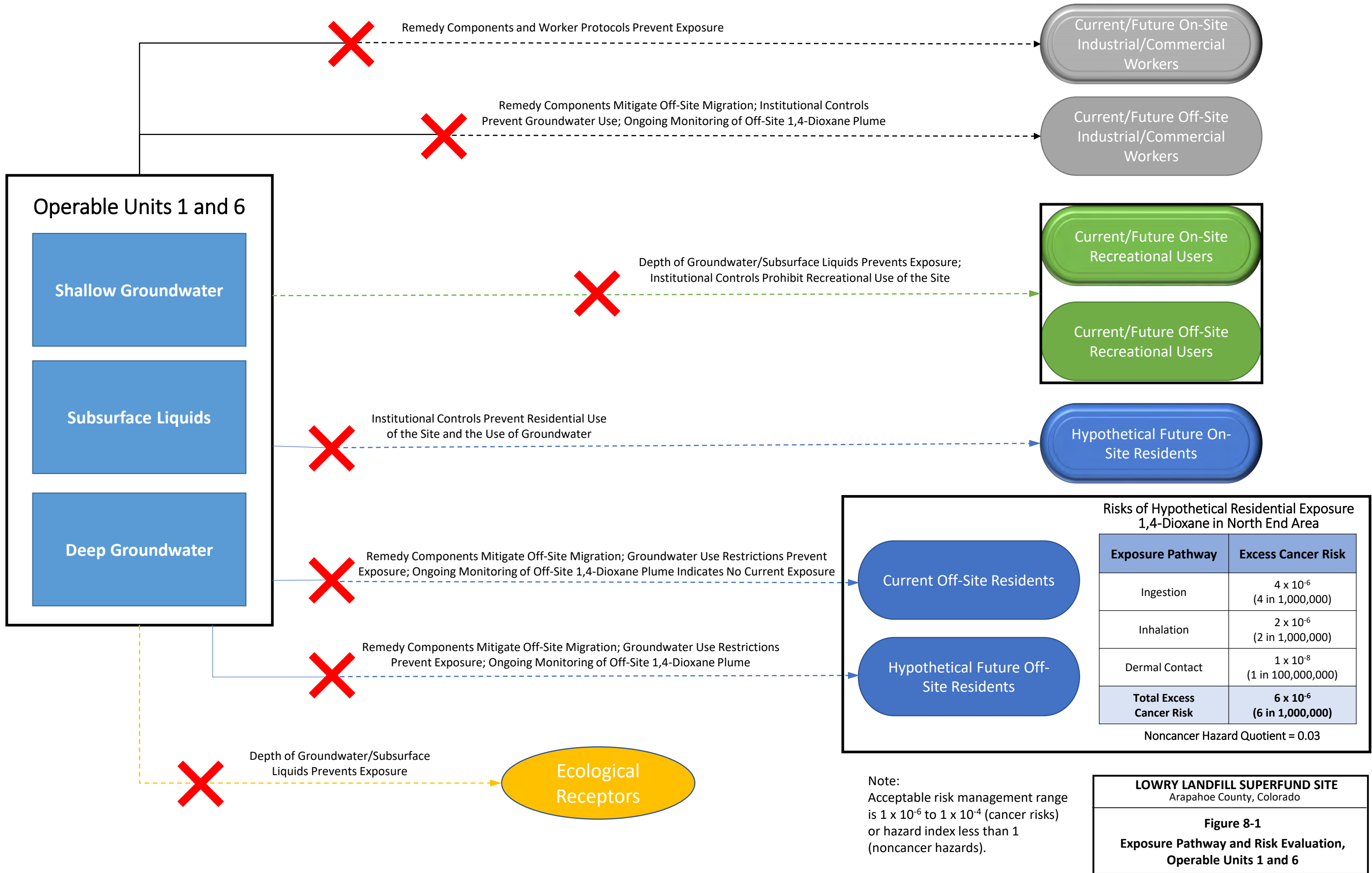
**Table 8-15. Risk Assessment Summary for Adult Recreational User (Golfer)**

Exposure Pathway	Excess Cancer Risk
Ingestion	$5 \times 10^{-9}$ (5 in 1,000,000,000)
Dermal Contact	$2 \times 10^{-11}$ (2 in 100,000,000,000)
<b>Total Excess Cancer Risk</b>	<b><math>5 \times 10^{-9}</math></b> <b>(5 in 1,000,000,000)</b>
<p>Notes:</p> <p>The noncancer hazard quotient was 0.0005.</p> <p>Because the golf course is open for approximately half a year, the risk evaluation assumes that an 80 kilogram golfer visits the course 45 times a year, plays the course in 6 hours, retrieves golf balls from the surface water in Murphy Creek exposing their hands, forearms, feet, and lower legs to the surface water for one hour (total skin surface area of 813 square centimeters), and incidentally ingests some of the surface water (0.11 liter each hour) each visit to the golf course for a total duration of 10 years.</p> <p>The acceptable risk management range is <math>1 \times 10^{-6}</math> to <math>1 \times 10^{-4}</math> (cancer risks) or hazard index less than 1 (noncancer hazards).</p>	



**Table 8-16. Risk Assessment Summary for Adolescent Recreational User**

Exposure Pathway	Excess Cancer Risk
Ingestion	$9 \times 10^{-9}$ (9 in 1,000,000,000)
Dermal Contact	$6 \times 10^{-10}$ (6 in 10,000,000,000)
<b>Total Excess Cancer Risk</b>	<b><math>1 \times 10^{-8}</math></b> <b>(1 in 100,000,000)</b>
<p>Notes:</p> <p>The noncancer hazard quotient was 0.00002.</p> <p>This risk exposure scenario assumes that an adolescent (age 6 to 16 years) weighing 44.3 kilograms would be playing in the surface water 45 days per year over a period of 10 years. Each time the individual plays in the water, it is assumed they will incidentally ingest small amounts of surface water (0.12 liter per hour) and also will be exposed through the skin (assuming a skin surface area of 13,350 square centimeters).</p> <p>The acceptable risk management range is <math>1 \times 10^{-6}</math> to <math>1 \times 10^{-4}</math> (cancer risks) or hazard index less than 1 (noncancer hazards).</p>	

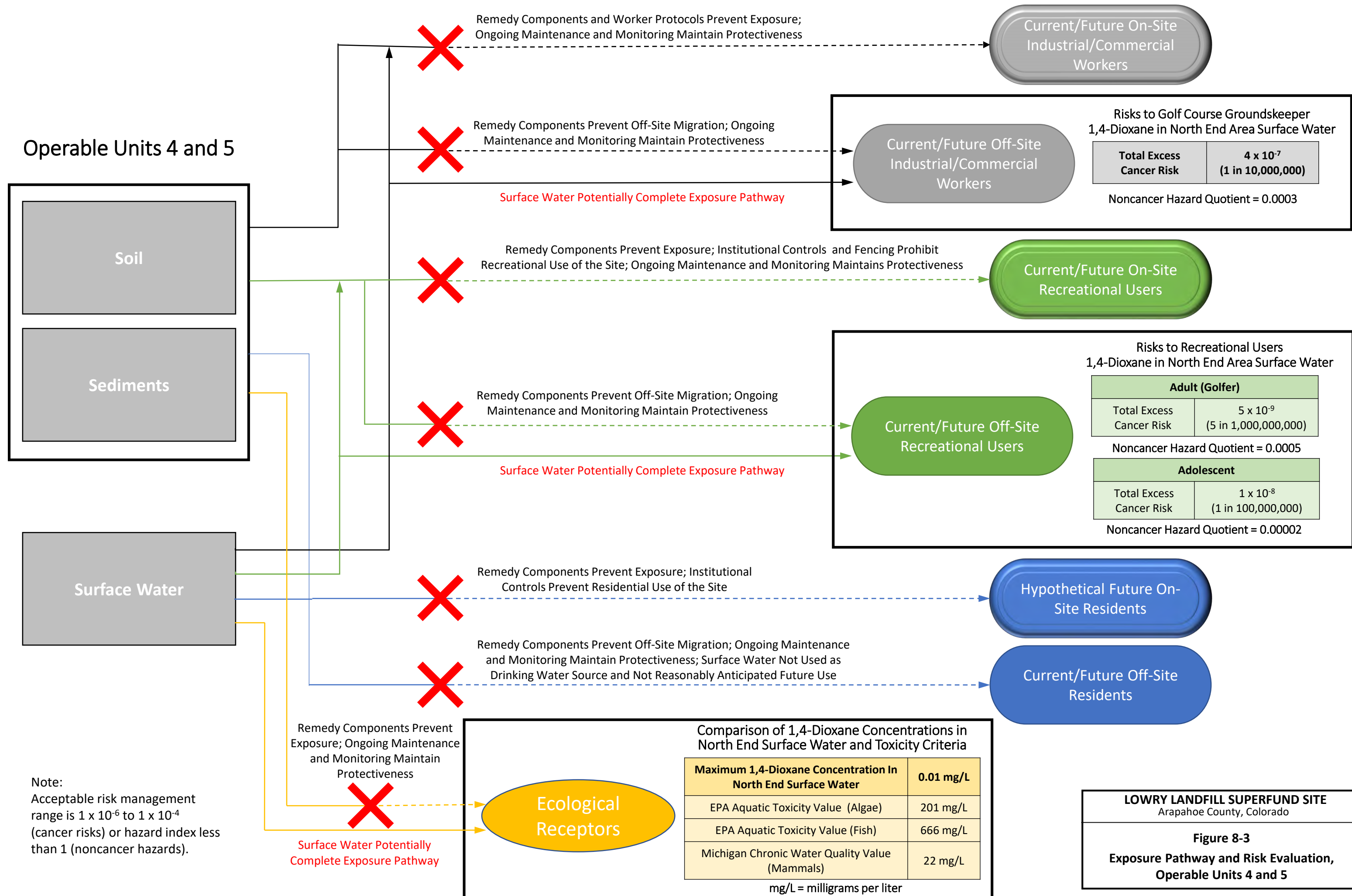




**LOWRY LANDFILL SUPERFUND SITE**  
Arapahoe County, Colorado

**Figure 8-2**  
**Exposure Pathway and Risk Evaluation,**  
**Operable Units 2 and 3**





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